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	Engineering and Design  HYDRAULIC DESIGN OF NAVIGATION LOCKS	
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EM 1110-2-1604  
30 June 1995

US Army Corps  
of Engineers

ENGINEERING AND DESIGN

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# Hydraulic Design of Navigation Locks

ENGINEER MANUAL

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DEPARTMENT OF THE ARMY  
U.S. Army Corps of Engineers  
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Engineering and Design  
HYDRAULIC DESIGN OF NAVIGATION LOCKS

**1-1. Purpose.** This manual presents the results of research, design studies, and operation experience as guidance for the hydraulic design of navigation locks.

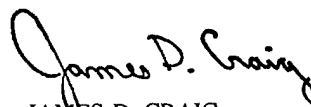
**1-2. Applicability.** This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for the design of civil works projects.

**1-3. General.** The guidance is limited to lock types that are considered design options by the U.S. Army Corps of Engineers (CE). Other designs, such as mechanical lifts and water slopes occasionally used in Europe, are discussed in Appendix G, but not in detail since they have not been feasible options for waterways within the United States. Detailed theory, computer programming, and computer codes are not presented; however, sources of these types of information are noted. The site, structure, hydraulic system, and operation of most existing CE lock configurations are summarized. Laboratory and field studies and other information data sources pertinent to these locks are identified. The overall broad scope of materials specifically addresses the following two design circumstances.

*a. Existing locks.* General information concerning hydraulic factors that tend toward safe, efficient, and reliable lock performance is directed toward repair or rehabilitation of existing locks. Many existing locks are not current state-of-the-art designs; design guidance for obsolete systems is not presented.

*b. New locks.* Detailed information regarding state-of-the-art hydraulic systems is directed toward new or replacement locks. General information regarding parameters used as the basis for design as well as specific information regarding function, structure, performance, and operation of modern locks is included.

FOR THE COMMANDER:

  
JAMES D. CRAIG  
Colonel, Corps of Engineers  
Chief of Staff

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Table of Contents

Subject	Paragraph	Page	Subject	Paragraph	Page
<b>Chapter 1</b>			<i>Section II</i>		
<b>Introduction</b>			<i>Navigation System Characteristics</i>		
<i>Section I</i>			Information and Data Required . . . .	2-5	2-1
<i>General</i>			Waterway . . . . .	2-6	2-1
Purpose . . . . .	1-1	1-1	Vessels . . . . .	2-7	2-3
Scope . . . . .	1-2	1-1	Commodities . . . . .	2-8	2-3
Applicability . . . . .	1-3	1-1	<i>Section III</i>		
References . . . . .	1-4	1-1	<i>Transit Time</i>		
Explanation of Terms . . . . .	1-5	1-1	Definition . . . . .	2-9	2-3
Technical Data . . . . .	1-6	1-1	Evaluation . . . . .	2-10	2-4
<i>Section II</i>			Chamber Performance . . . . .	2-11	2-4
<i>Technical Coordination</i>			Application . . . . .	2-12	2-4
General . . . . .	1-7	1-2	<i>Section IV</i>		
Automatic Data Processing (ADP) . . .	1-8	1-2	<i>Chamber Alternatives</i>		
WES Capabilities and Services . . . .	1-9	1-2	General . . . . .	2-13	2-5
Design Memorandum Presentations . .	1-10	1-2	Number of Parallel Chambers . . . .	2-14	2-5
<i>Section III</i>			Chamber Dimensions . . . . .	2-15	2-5
<i>Project Function</i>			Chamber Types . . . . .	2-16	2-5
General . . . . .	1-11	1-2	<i>Section V</i>		
Primary Components . . . . .	1-12	1-2	<i>Foundation and Structure Concerns</i>		
Special Needs . . . . .	1-13	1-4	Hydraulic Loading . . . . .	2-17	2-6
Classification Systems . . . . .	1-14	1-4	Chamber Structure . . . . .	2-18	2-6
CE Lock Operating Experience . . . .	1-15	1-4	Guide and Guard Walls . . . . .	2-19	2-7
<b>Chapter 2</b>			Other Structures . . . . .	2-20	2-10
<b>Project Identification</b>			<b>Chapter 3</b>		
<i>Section I</i>			<b>Hydraulic Features</b>		
<i>Design Management</i>			<i>Section I</i>		
General . . . . .	2-1	2-1	<i>Filling and Emptying</i>		
Design Constraints . . . . .	2-2	2-1	Project Type . . . . .	3-1	3-1
Incremental Effects . . . . .	2-3	2-1	Design Type . . . . .	3-2	3-1
General Studies . . . . .	2-4	2-1	Lateral Culverts . . . . .	3-3	3-2

Subject	Paragraph	Page
Features .....	3-4	3-3
Recent Designs .....	3-5	3-3
<i>Section II</i>		
<i>Appurtenant Concerns</i>		
General .....	3-6	3-4
Navigation Aids .....	3-7	3-4
Surge Reduction .....	3-8	3-4
Impact Barriers .....	3-9	3-4
Water Saving .....	3-10	3-4
Dewatering .....	3-11	3-4
Emergency Closure .....	3-12	3-4
Debris Control .....	3-13	3-5
Ice Control .....	3-14	3-5

## Chapter 4 Filling-and-Emptying Feature Design

<i>Section I</i>		
<i>Preliminary Calculations</i>		
General .....	4-1	4-1
Sill Spacing Parameters .....	4-2	4-1
Sill Spacing .....	4-3	4-2
Location of Intake Structures .....	4-4	4-2
Lock Filling .....	4-5	4-2
Chamber Depth .....	4-6	4-3
Sill Elevation .....	4-7	4-3
Sill Elevation Guidance .....	4-8	4-3
Location of Outlet Structures .....	4-9	4-6
Typical Outlet Locations .....	4-10	4-6
<i>Section II</i>		
<i>Very-Low-Lift Designs</i>		
General .....	4-11	4-7
Sector Gate Design Concept .....	4-12	4-7
Hydraulic Evaluation .....	4-13	4-7
Side-port Flume (SPF) Designs .....	4-14	4-8
<i>Section III</i>		
<i>Culvert-to-Chamber Systems</i>		
General .....	4-15	4-8
Chamber Port Arrangements .....	4-16	4-8
Flow Passage Areas .....	4-17	4-9
Chamber Ports, Baffles, and Manifolds .....	4-18	4-9
<i>Section IV</i>		
<i>Outlet Systems</i>		
General .....	4-19	4-11
Design Types .....	4-20	4-11

<i>Section V</i>		
<i>Intakes</i>		
General .....	4-21	4-12
Design Types .....	4-22	4-12
<i>Section VI</i>		
<i>Filling-and-Emptying Valve Systems</i>		
General .....	4-23	4-13
Valve Sizing .....	4-24	4-13
Valve Siting .....	4-25	4-13
<i>Section VII</i>		
<i>Culvert Layouts</i>		
General .....	4-26	4-14
Contracting and Expanding Systems .....	4-27	4-14
Other Transitions .....	4-28	4-14

## Chapter 5 Special Hydraulic Study Topics

<i>Section I</i>		
<i>Introduction</i>		
Baseline Analysis .....	5-1	5-1
Baseline Constraints .....	5-2	5-1
Analysis Results .....	5-3	5-1
<i>Section II</i>		
<i>Steady Flow in Lock Culverts</i>		
Discharge .....	5-4	5-1
Energy Loss Coefficient .....	5-5	5-2
Individual Losses .....	5-6	5-2
Reynolds Number .....	5-7	5-2
Energy-Loss Coefficient Values .....	5-8	5-2
<i>Section III</i>		
<i>Lock Filling and Emptying</i>		
General Features .....	5-9	5-5
Valve Operation .....	5-10	5-5
Lock Coefficient .....	5-11	5-5
Operation Time Estimates .....	5-12	5-7
Basis For Numerical Simulations .....	5-13	5-7
Mathematical Aids .....	5-14	5-8
<i>Section IV</i>		
<i>Culvert Features</i>		
Goals .....	5-15	5-9
Improved Performance .....	5-16	5-9
Evaluation .....	5-17	5-9

Subject	Paragraph	Page
<i>Section V</i>		
<i>Valve Hydraulic Characteristics</i>		
Design Concerns .....	5-18	5-9
Valves With Expansions		
Downstream .....	5-19	5-10
<i>Section VI</i>		
<i>Low Pressure Effects</i>		
General Concerns .....	5-20	5-10
Reverse Tainter Valves .....	5-21	5-10
<i>Section VII</i>		
<i>Air Inflow and Outflow Devices</i>		
High-Lift Lock Air Vents .....	5-22	5-10
Low-Lift Lock Air Vents .....	5-23	5-11
<i>Section VIII</i>		
<i>Vorticity at Intakes</i>		
General .....	5-24	5-11
Evaluation .....	5-25	5-11
<i>Section IX</i>		
<i>Energy Dissipation at Outlets</i>		
Conditions .....	5-26	5-11
Options .....	5-27	5-12
<b>Chapter 6</b>		
<b>Hydraulic Model Studies</b>		
<i>Section I</i>		
<i>Introduction</i>		
General .....	6-1	6-1
Purpose of Model Study .....	6-2	6-1
Scales .....	6-3	6-1
Model and Prototype Similarities .....	6-4	6-1
Model Construction .....	6-5	6-2
Instrumentation .....	6-6	6-2
Pressure Measurements .....	6-7	6-2
<i>Section II</i>		
<i>Prototype Expectations</i>		
General .....	6-8	6-4
Revisions to Scaled Values .....	6-9	6-4
<i>Section III</i>		
<i>CE-Sponsored Hydraulic Model and Prototype Studies</i>		
Database .....	6-10	6-4
<b>Chapter 7</b>		
<b>Other Hydraulic Design Features</b>		
Scope .....	7-1	7-1

Subject	Paragraph	Page
<i>Section I</i>		
<i>Surge Reduction</i>		
Solutions .....	7-2	7-1
Computational Aids .....	7-3	7-1
<i>Section II</i>		
<i>Impact Barriers</i>		
Purpose .....	7-4	7-1
<i>Section III</i>		
<i>Water Saving</i>		
Water Supply .....	7-5	7-1
Design Needs .....	7-6	7-2
<i>Section IV</i>		
<i>Dewatering</i>		
Concerns .....	7-7	7-2
Coordination .....	7-8	7-2
<i>Section V</i>		
<i>Emergency Closure</i>		
General Emergency Situations .....	7-9	7-2
Consequences of Pool Loss .....	7-10	7-2
Preliminary Studies .....	7-11	7-2
Types of Closure Systems .....	7-12	7-2
Design Loadings .....	7-13	7-4
<i>Section VI</i>		
<i>Ice Control at Locks</i>		
Types of Ice .....	7-14	7-4
Ice Problems .....	7-15	7-4
Air Screen .....	7-16	7-4
Lock Wall De-icing .....	7-17	7-5
Lock Gate and Valve De-icing .....	7-18	7-6
Considerations for Rehabilitation and New Construction .....	7-19	7-6
<i>Section VII</i>		
<i>Repair and Rehabilitation</i>		
Purpose and Scope .....	7-20	7-6
Reliability Improvement .....	7-21	7-6
Efficiency Improvement .....	7-22	7-7
Threshold Amounts .....	7-23	7-7
Typical Study Items .....	7-24	7-7
<i>Section VIII</i>		
<i>Environmental Concerns</i>		
Effect of Lock .....	7-25	7-8
Water Quality .....	7-26	7-8
Recreational Craft .....	7-27	7-8
Facility Alternatives .....	7-28	7-8
Second Lock Chamber .....	7-29	7-8

**EM 1110-2-1604**

**30 Jun 95**

<b>Subject</b>	<b>Paragraph</b>	<b>Page</b>	<b>Subject</b>	<b>Paragraph</b>	<b>Page</b>
<b>Appendix A References</b>			<b>Appendix E Design of High-Lift Locks</b>		
<b>Appendix B Inventory of Existing Locks</b>			<b>Appendix F Computer Runs</b>		
<b>Appendix C Lock Hydraulic System Model and Prototype Study Data</b>			<b>Appendix G Mechanical Lifts</b>		
<b>Appendix D Design of Side-port Systems</b>			<b>Appendix H Notation</b>		



## Chapter 1 Introduction

### Section I General

#### 1-1. Purpose

This manual presents the results of research, design studies, and operation experience as guidance for the hydraulic design of navigation locks.

#### 1-2. Scope

The guidance is limited to lock types that are considered design options by the U.S. Army Corps of Engineers (CE). Other designs, such as mechanical lifts and water slopes occasionally used in Europe, are discussed in Appendix G, but not discussed in detail since they have not been feasible options for waterways within the United States. Detailed theory, computer programming, and computer codes are not presented; however, sources of these types of information are noted. The site, structure, hydraulic system, and operation of most existing CE lock configurations are summarized. Laboratory and field studies and other information data sources pertinent to these locks are identified. The overall broad scope of materials specifically addresses the following two design circumstances.

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#### 1-3. Applicability

This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for the design of civil works projects.

#### 1-4. References

Appendix A groups references into three lists: the Required Publications and Related Publications consisting of CE-Sponsored Lock Hydraulic System Study Reports and General Bibliography. Each list is discussed below.

*a. HQUSACE Publications.* Applicable Corps guidance including Engineering Regulations, Engineering Manuals etc., are listed in numerical order in Appendix A, paragraph A-1. References throughout the manual use the document number.

*b. CE-Sponsored Lock Hydraulic System Study Report.* These reports are U.S. Army Corps of Engineers sponsored laboratory studies of lock systems administered by Waterways Experiment Station (WES), Bonneville Hydraulics Laboratory (BHL), or St. Paul District (STP). References throughout the manual begin by a number (e.g. item 01, item 02, ..., item 86). Corresponding references are listed chronologically in Appendix A, paragraph A-2.

*c. General Bibliography.* These references include other general literature relevant to hydraulic design of navigation locks or applicable hydraulic topics. References throughout the manual begin with a letter (first letter of the author's last name) followed by a number (e.g., A1, A2, B1, B2, etc). Corresponding references are listed in alphabetical order by author in Appendix A, paragraph A-3.

#### 1-5. Explanation of Terms

Symbols used throughout this manual are defined in Appendix H and, as far as practical, conform to the American Standard Letter Symbols for Hydraulics (item A4). Symbols are also defined at the first use within the text.

#### 1-6. Technical Data

Plates at the end of the appropriate chapter provide design guidance and details for hydraulic design. Data sources are identified. A summary of existing CE locks including various arrangements of hydraulic features is presented in Appendix B and in more detail in the CEWRC-NDC Waterling Bulletin Board System (Navigation and Dredging Data and Reports, Lock Characteristics Data, Physical Characteristics Report).

30 Jun 95

*Section II**Technical Coordination***1-7. General**

Specific services are available to the designer in subject areas complementary to the hydraulic design. These are not, in general, described in this manual. Centers of expertise addressing environmental topics, hydropower, navigation, etc., may be located by query to HQUSACE.

**1-8. Automatic Data Processing (ADP)**

The development and management of computer-based capabilities is an ongoing process within the CE. ADP coordinators at HQUSACE, Division, District, and Research offices may be queried with regard to program and equipment status. The WES Automatic Data Processing Center (ADPC) Computer Program Library (WESLIB) provides computer information and services to CE Divisions and Districts. One service is the Conversationally-Oriented Real-Time Programming System (CORPS), which provides a set of proven engineering applications programs that can be accessed on several different computer systems by engineers with little or no computer training. A catalog of WESLIB programs is maintained (updated as needed) and distributed to ADP users throughout the CE. References to programs available to the lock designer are noted in this manual by the CORPS program number.

**1-9. WES Capabilities and Services**

WES has capabilities and furnishes services in the fields of hydraulic modeling, analysis, design, and prototype testing. Expertise has been developed in the areas of water quality studies, mathematical modeling, and computer programming. Procedures necessary to arrange for WES participation in hydraulic studies of all types are covered in Engineer Regulation (ER) 1110-1-8100. WES also has the responsibility for coordinating the CE hydraulic prototype test program. Assistance during planning and testing is included in this program.

**1-10. Design Memorandum Presentations**

Design memoranda should contain sufficient information to ensure that the reviewer is able to reach an independent conclusion as to the design adequacy. For convenience, the hydraulic information, factors, studies, and logic used to establish such basic features as type of lock intake, manifold system, outlet, valves, etc., should be complete and readily identifiable within the hydraulics

presentation. Appurtenant items such as debris barriers and emergency closure procedures should be presented in similar detail. Operating characteristics over the full range of hydrologic, navigation, and other site-specific boundary conditions should be provided.

*Section III**Project Function***1-11. General**

The function of a lock is to provide safe passage for navigation between two pools not at the same water level. The difference in water level may exist naturally (as in the Panama Canal Locks) or be developed for economic reasons (such as hydropower at Bonneville Lock on the Columbia River or navigation at Bay Springs Lock on the Tennessee-Tombigbee Waterway). Other considerations (economic, environmental, geotechnical, etc.) are constraints to the design process. Site-specific constraints, including those that for practical reasons are beyond the scope of this manual, should be clearly stated in hydraulic presentations.

**1-12. Primary Components**

All lock designs presented in this manual contain the four primary components given below and shown schematically in Figure 1-1.

*a. Upper approach.* The canal immediately upstream from the lock is referred to as the upper approach. The guide wall serves to align and to guide a downbound tow into the lock chamber and is usually a prolongation of one wall of the chamber. The guard wall provides a barrier that prevents the tow from entering an area having hazardous currents or potentially damageable or damaging structures. The term guide-and-guard wall may be used when the combination of functions results in deviations from usual guide wall design practice. Guidelines for approach channel design are included in EM 1110-2-1611.

*b. Lock chamber.* The downbound traffic is lowered to lower pool and the upbound traffic is raised to upper pool within the lock chamber. The upper and lower gates are movable barriers that can be opened to permit a vessel to enter or exit the chamber. Sills, which extend across the lock chamber at the base of the gates, provide a surface for gate closure and are the structural limits for navigable depth in the lock. Lock wall appurtenances are

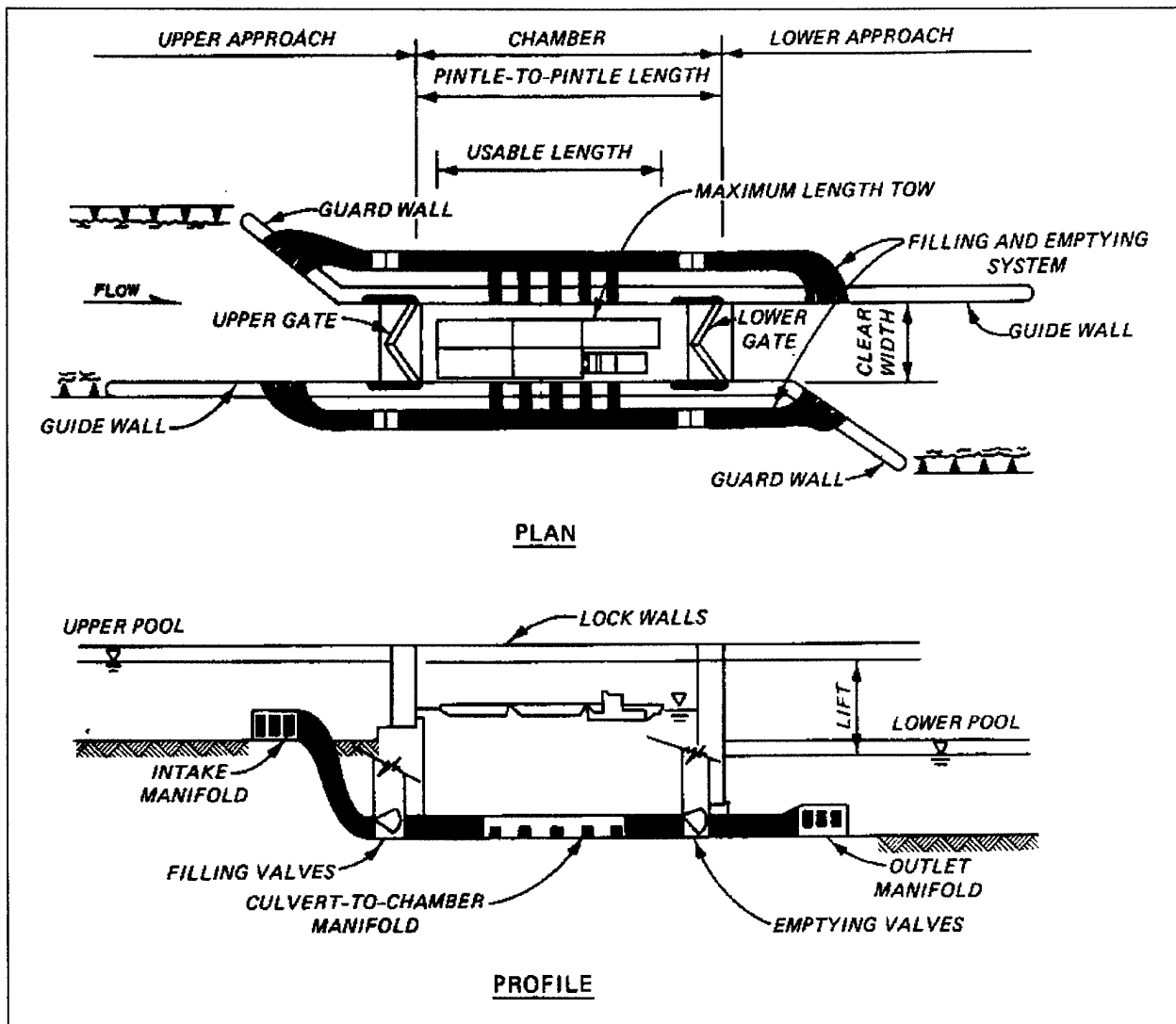


Figure 1-1. Common lock features for a lock with culverts in the sidewall

recessed so that the clear width and the usable width are identical. Conversely, because of clearances provided for gate operation and for longitudinal tow drift, the usable length of the chamber differs from commonly specified nominal lengths, i.e., less than the pintle-to-pintle length shown in Figure 1-1. The difference between upper and lower pool elevations is termed lift.

*c. Filling and emptying system.* For a lock filling operation, the emptying valves are closed. The filling valves are opened. Flow enters the intake manifolds and exits by means of the culvert-to-chamber manifolds into the lock chamber. For emptying, the filling valves are

closed and the emptying valves are opened. Flow enters the culvert-to-chamber manifolds and exits by means of the outlet manifolds. Many differences are possible and acceptable between the idealized system shown in Figure 1-1 and an actual design. Intakes and outlets may not be located directly in the approach canals; the number, general shape, and location of the manifolds vary between designs; the filling-and-emptying system may be separated; etc.

*d. Lower approach.* The canal immediately downstream from the chamber is referred to as the lower approach. Guide, guard, and guide-and-guard walls are

used and defined similarly both upstream and downstream from the lock (EM 1110-2-1611).

### 1-13. Special Needs

Operation and maintenance considerations (as well as more site-specific topics such as environment, relocations, and geotechnical factors) require additions to the schematized navigation lock shown in Figure 1-1. Construction cofferdams, emergency closure devices, surge suppression pools, and impact barriers are examples of more common special needs that are studied during hydraulic design of navigation locks.

### 1-14. Classification Systems

Two methods are used to classify lock projects.

*a. Project classification (lift).* etc.) within the chamber to obtain smooth filling and emptying. In addition, higher lifts require the filling-and-emptying system to be designed such that cavitation, abrasion, flow-induced vibration, and other liabilities associated with high-velocity flow do not occur. A lock project is therefore viewed by lift as being in one of four categories as identified from studies of existing projects (Plate 1-1). The categories are listed in Table 1-1.

*b. Design classification (filling-and-emptying systems).* Specifications regarding within-chamber manifolds, baffles, and other structural elements are derived from laboratory testing and prototype experience. Small variations in these elements, particularly for high-lift locks, may cause significant surface currents or local turbulence unfavorable to lock operation. Two specific design alternatives are suggested in this manual for each range of project lifts. Schematics of the suggested designs are shown in Figure 1-2 and comments regarding their applicability are included in Table 1-1. Higher lift designs function well at lower lifts; however, increased costs are also associated with higher lift designs.

### 1-15. CE Lock Operating Experience

A list of most existing CE locks is in Appendix B. Plate 1-1 illustrates the historic trend away from certain designs (i.e., loop culverts and valves-in-gates) reflecting economic or operational liabilities. Substantial experience with sector gate (very-low-lift) and side-port (low-lift) designs is evident. One each of the longitudinal manifold (vertically divided flow by means of horizontal splitters) designs suggested for high-lift projects is in operation. An extensive summary of devices and concepts used in earlier (pre-1940) CE navigation locks and dams is available (item U1).

**Table 1-1**  
**Classification of Projects by Lifts**

Range of Maximum Design Lift (ft to ft)	Project Classification	Percent of Corps Locks	Suitable Design Types
0 <sup>+</sup> to 10	Very low lift	25	End filling-and-emptying systems are suitable. Each of the three general types (gate, valve(s)-in-gate, and loop culvert) can normally provide satisfactory chamber conditions. Choice of type is influenced by economic, operational, and layout factors. The sector gate has been used exclusively for CE very-low-lift designs since 1950.
10 to 30/40	Low lift	60	Wall culverts with side ports (side-port systems) are generally best suited for lifts below about 30 ft. The auxiliary system using lateral manifolds is suitable for low-lift projects requiring one culvert lock operation. Simplified high-lift designs have been model-tested for lifts in the 30- to 40-ft range.
30/40 to 100	High lift	15	Longitudinal manifold systems are suitable. Choice of type (4 or 8 manifolds) is influenced by economic and layout factors. Recent designs subdivide the flow by means of horizontal rather than vertical piers.
100 to ____ (Undefined)	Very high lift	0	These projects are outside the range of CE lock operational experience (Plate 1-1); the exception in John Day Lock (107-ft lift) on the Columbia River. High-lift designs augmented by analytical and laboratory studies are suggested for preliminary (prior to physical model testing) layout.

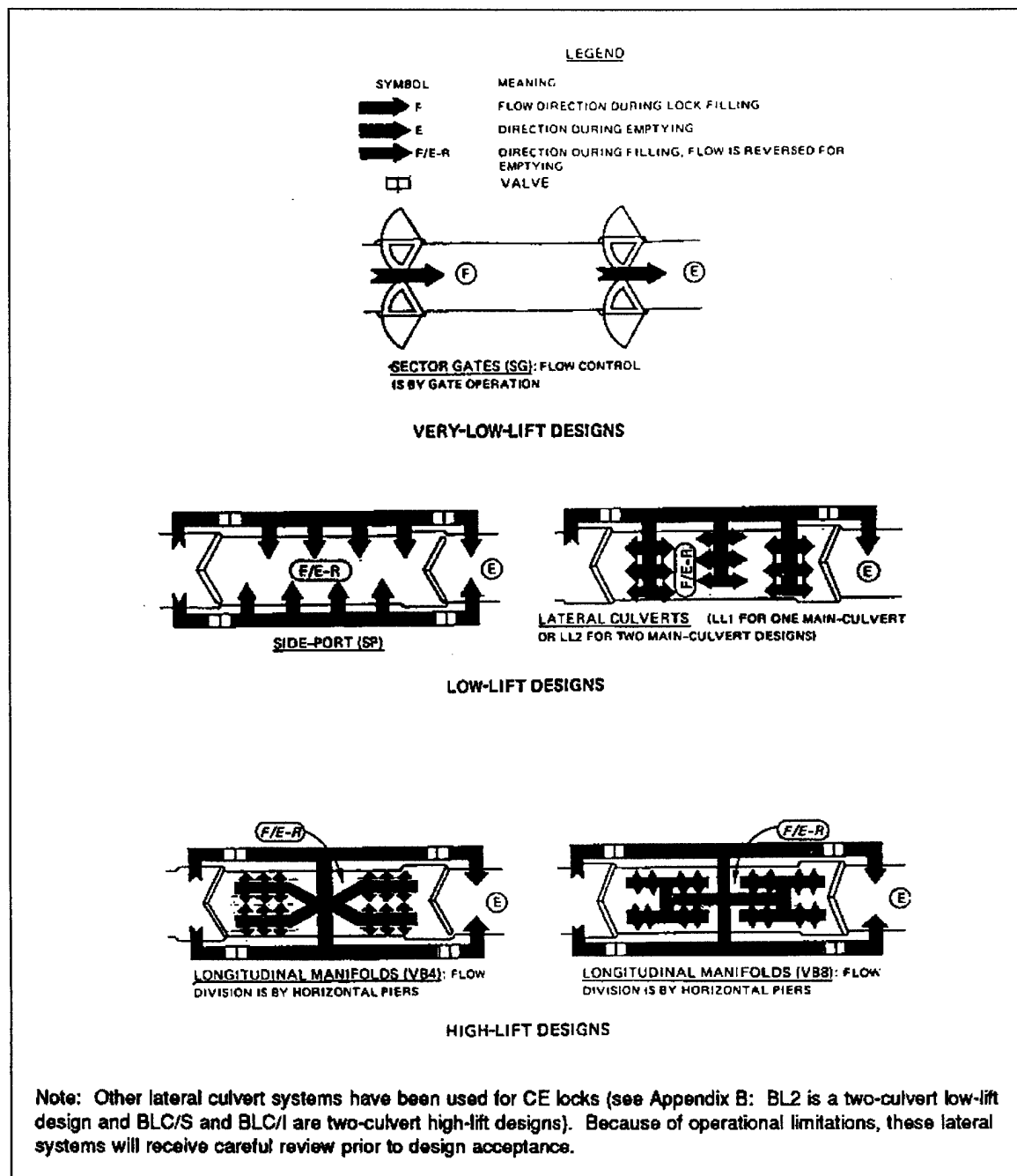
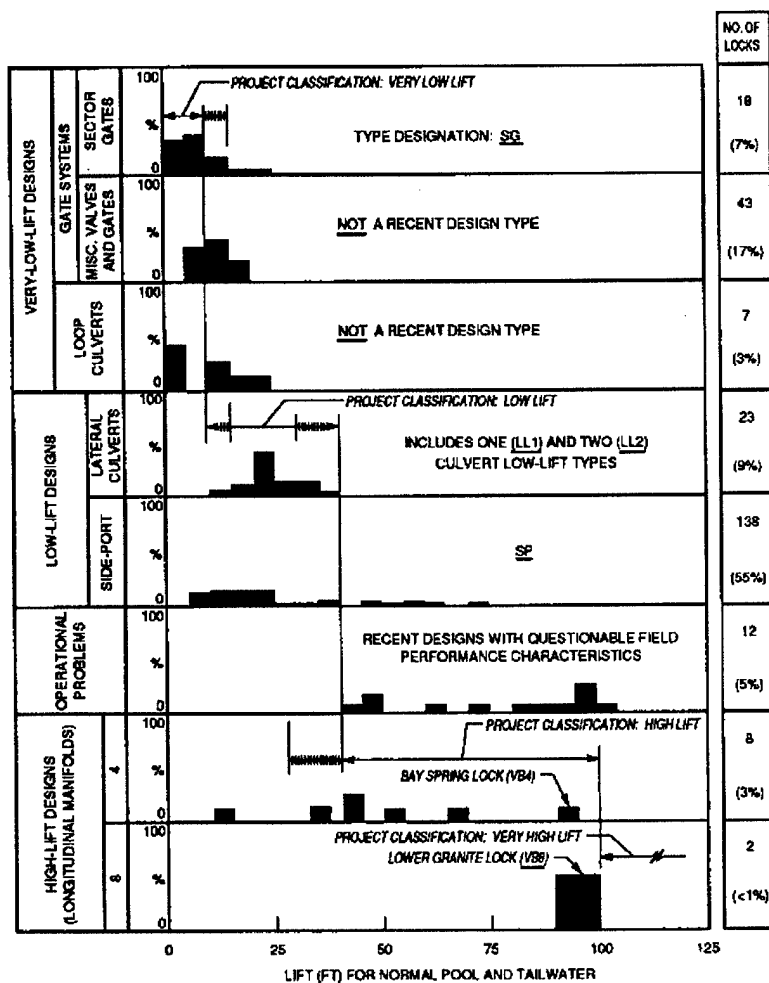


Figure 1-2. Flow distribution of recommended designs



TOTAL SAMPLE = 251

- NOTES:
1. DESIGN DETAILS VARY WITHIN EACH DESIGN TYPE.
  2. ORDINATE PERCENTAGES ARE PER DESIGN TYPE.
  3. ABSCISSA (LIFT) INCREMENT IS 5 FT.
  4. REPORTING PROCEDURE (LIFT AND TYPE) IS IMPRECISE; ALL CE LOCKS ARE NOT INCLUDED.
  5. REFER TO EP1105-2-11 AND APPENDIX B FOR PROJECT INFORMATION.
  6. ■■■■■ INDICATES OVERLAPPING OF DESIGN TYPES.

## HISTOGRAMS CE LOCK OPERATION EXPERIENCE

PLATE 1-1

## Chapter 2 Project Identification

### Section I Design Management

#### 2-1. General

Lock design is a multidisciplinary activity. Coordination among disciplines is initiated prior to hydraulic design of the filling-and-emptying system and is continued throughout the design process. Capacity and economic studies precede project authorization so that general guidance for *location, lockage time, lift variations, number of chambers, design vessel, usable length, and clear width* is available at the onset of hydraulic feature design. Capacity concerns (items B7, D5, D7, D10, E2, F2, G1, K1, K2, L1, S2, and S5) are dynamic as quality, size, and timeliness of database content and computer software and hardware capabilities change. Two WES studies (items D1 and D2) are examples of computer-based analysis of inland waterway systems. Guidance and assistance for these studies were from the Navigation Support Center (ORLPD-C), U.S. Army Engineer District, Louisville.

#### 2-2. Design Constraints

Table 2-1 lists selected preliminary topics that influence the hydraulic design of locks. These topics, termed constraints herein, are documented prior to design. The source or cause of each constraint and, where appropriate, physical and economic values are included in the documentation. Design time is reduced when constraints are well-defined and conflicts between constraints are resolved in a timely manner. Site-specific constraints are reviewed and quantified prior to hydraulic design. Environmental issues are often site-specific due to differences in the impacts of climate, water quality, economic development, and many other factors on local ecology. Macrofouling by the nonindigenous zebra mussel (*Dreissena polymorpha*) is an example. Information regarding the effects of zebra mussel infestation is available as technical notes, workshop proceedings, and other databases. These are available from the U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-ER-A, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

#### 2-3. Incremental Effects

Certain factors, such as number of chambers, when incremented are a major change in project concept and are not included in feature design. Other factors, such as

operation time, may be varied by the design process to increase benefits but must be economically balanced with the increase in cost. Information regarding relative unit costs of property, operational efficiencies, and structural elements can be used to develop cost-effective projects.

#### 2-4. General Studies

The numerous multidisciplinary studies that precede hydraulic design are beyond the scope of this manual. However, the following sections summarize four study topics that commonly are used to resolve most constraints listed in Table 2-1: navigation system studies concern the interdependency of waterway, vessel, and commodity characteristics; navigation transit time studies concern the problem of expeditiously moving vessels through the project; chamber alternatives studies derive optimum chamber dimensions and number of chambers based on economic and physical factors; and geotechnical and structural studies tend to identify chamber location and type of structure.

### Section II Navigation System Characteristics

#### 2-5. Information and Data Required

Navigation systems are addressed in the National Waterways Study (item U2) and other transportation-planning reports (item 58, for example). The studies quantify constraints imposed by standardization as well as by the system-wide transportation function. Near-project constraints concerning layout and location are described in EM 1110-2-1611 for shallow-draft waterways and in EM 1110-2-1613 for deep-draft waterways.

#### 2-6. Waterway

The physical characteristics of a waterway such as width, depth, and bend radii limit the types of traffic that can use the channels. The type of traffic, in turn, influences the design of any lock. The Great Lakes connecting channels, the St. Lawrence Seaway, channels in estuaries, and several channels contiguous to the coast are deep enough for vessels drawing 27 to 35 feet (ft). Shallow river channels and canals limit the traffic to shallow-draft tows and pleasure craft: 14 ft, Columbia River, is the maximum design draft for U.S. tows; 9 ft, Ohio River and others, is a more common limit. Overviews of navigation systems are available (items S8 and U2). Reviews of channel development for these systems are also available (EM 1110-2-1611 and items H2 and F4). Examples of published reviews for specific systems are as follows:



**Table 2-1**  
**Examples of Constraints Considered During Hydraulic Design of Locks**

Scope	Type of Constraint	Scope	Type of Constraint
Authorization	Type (New Design, Rehabilitation, Replacement) Funding Capacity Economics Other Authorization Requirements	Project	Multipurpose Functions Compatibility (Navigation) Compatibility (Flows) Lock Chamber Location Approach Channel Layout
System	Economics/Standardization Number of Parallel Chambers Clear Width Usable Length Lockage Procedures Appurtenant Equipment Emergency Procedures  Vessel Characteristics Design Type (Shape, Length, Width, Draft) Vessel Mix  Hydrology Projected Distribution of Flows Extreme (High and Low) Flows Ice and Debris Management  Navigation Navigation Limits Special Needs  Other System Requirements		Hydrologic/Operational Projections Upper Pool (Maximum, Minimum, Design) Lower Pool (Maximum, Minimum, Design) Lock Status During Extreme Flows  Lock-Structure Design Requirements Geotechnical (Foundations, etc.) Structural (Monolith Design, etc.) Electrical-Mechanical (Power Supply, etc.)  Archeologic, Historic, and Environmental Requirements  Operational Needs Lockage Procedures Emergency Closure Deicing (Chamber and Equipment) Debris and Ice Control Inspection and Maintenance Safety Other Operational Needs  Construction Closure or Diversion Lock Status  Property Relocations Acquisitions and Easements  Other Site-Specific Concerns

**Note:** This listing of constraints is not exhaustive. A site-specific situation may require any item to be rigid, flexible, minor, or nonexistent. Many constraints require relative-cost studies of alternate workable schemes. The resolution of conflicts between constraints is a major part of lock design management. *Primary Function = Navigation Capacity*

- a. St. Lawrence Seaway (items B12 and D3).
- b. Upper Mississippi (L&D) River (item D8).
- c. New York State Barge Canal (item H7).
- d. Great Lakes (item M3).
- e. Lower Cumberland (item D14).
- f. Columbia River (item H3).
- g. Mississippi and Gulf Coast (item M11).
- h. Welland Canal (item 02).

## 2-7. Vessels

Decisions regarding depth on the lock sills, size of chambers, guide wall layout, and to some extent the type of filling system are influenced by the types of vessels that will use the waterway. For example, recreational traffic uses locks designed for either shallow-draft (barge) or deep-draft (large ship) traffic, but there are conflicting requirements for locks that are to be used by *both* barge tows and large ships--over 75,000 deadweight tons (dwt). Maximum values of length, width, and draft are of particular concern. Larger tows are of concern in that the extent of breaking and making of tows influences decisions regarding general lock operational procedures as well as tie-up and fleeting area design. Reviews of vessel characteristics are available (items G4, S8, and U2) and are to some extent included in discussions regarding lock sizes (items B6 and D6) and vessel equipment (items D13 and H5). The contrast between barges used for the Ohio River and connecting systems (items C2 and M9) and the Columbia River system (item T1) illustrates the effect of commodity type on the commercial carrier design. Detail from these and similar reviews, because of timeliness, requires verification prior to inclusion in the design process.

## 2-8. Commodities

The economic studies required for lock authorization use tonnage projections that are developed through economic studies of past, present, and future commodity movements. Most engineering impacts of commodity type are resolved by studies of vessel characteristics (paragraph 2-7); certain concerns, such as the dominance of downbound versus upbound loads or the presence of hazardous or otherwise sensitive cargos, may be site-specific operational concerns.

## Section III Transit Time

### 2-9. Definition

The annual tonnage that can be passed through a project is influenced by

- a. Time required for tows to transit the locks (transit time).
- b. Number and size of lock chambers.
- c. Average tonnage per tow.
- d. Number of days per year that the locks can physically operate.
- e. Percentage of time that tows are available for lockage.
- f. Cost of delays to tows waiting lockage.

Transit time (*a* above), derived from capacity/economic studies, becomes a specific design objective; chamber option (*b* above), similarly derived, is a design constraint not usually altered by the design process; other factors (*c-f* above) are system characteristics. Transit time is defined as the total time required for a tow to move into a lock from a waiting point (arrival point), be raised or lowered, and then proceed out of the lock to a position where it will not interfere with any other tow that needs to transit the lock. Transit time includes

- a. Time required for a tow to move from an arrival point to the lock chamber.
- b. Time to enter the lock chamber.
- c. Time to close the gates.
- d. Time to raise or lower the lock surface (fill or empty).
- e. Time to open the gates.
- f. Time for the tow to exit from the chamber.
- g. Time required for the tow to reach a clearance point so that another tow moving in the opposite direction can start toward the lock.

*h. Time required for break down, locking through, and reassembling a tow that is too large for the lock chamber.*

The objective in the overall planning of a lock project (capacity/economic studies) is to establish a value for transit time commensurate with authorization constraints (paragraph 2-2).

## 2-10. Evaluation

Two of the eight time components listed in paragraph 2-9 (gate operating time and filling and emptying time) are entirely dependent on the design of the lock. Approach time, entry time, exit time, and departure time are dependent on pilot skill and towboat capability and on design of approach channels, guide walls, and lock chambers. For a single lockage at modern locks, operation time constitutes only about 25 to 40 percent of the total transit time. The Performance Monitoring System is a CE-maintained database established for the purpose of monitoring parameters relative to the economic analysis of navigation locks. Transit time components are available for many existing locks in this database. Guidance regarding the Performance Monitoring System is available in Headquarters' Operations, Construction and Readiness Division, Dredging and Navigation Branch.

## 2-11. Chamber Performance

During hydraulic design, meeting the project capacity economic constraint requires reducing the time, termed operation time, required to fill or empty the chamber to a value equal to or less than the value used for project authorization. The within-chamber navigation constraint on rapid filling is termed chamber performance; acceptable chamber performance is normally studied by means of filling-and-emptying operations in small-scale physical hydraulic models as discussed in Chapter 6. Typical observations are as follows:

*a. Surface currents and turbulence.* Acceptable performance requires that surface turbulence hazardous to small vessels be identified and to the extent possible eliminated.

*b. Drift of free tows.* The movement of unmoored vessels (from the traffic mix) must be acceptable to navigation and lock operations and not be hazardous to either vessels or structure.

*c. Hawser forces.* Mooring line stresses required to restrain the vessel from longitudinal and lateral movement must be acceptable to navigation and to

structural design. Specific numerical limiting values have been placed on model hawser stresses. The historic development is based on breaking strength of one used 2.5-inch (in.)-diameter manila hawser: a 10,000-pound (lb) loading has been used as a safe nonbreaking value. Many years of prototype observation and model testing have shown that when a lock is designed not to exceed the hawser stresses given in (1)-(3) below as determined in a model, the prototype mooring conditions will be satisfactory for the design vessel as well as for small craft.

(1) *Barge tows.* For various sizes and numbers of barges in any location in the lock chamber, the hawser stress as extrapolated from a model does not exceed 5 tons (2,000-lb tons).

(2) *Single vessels--ships up to 50,000 tons.* Hawser stress does not exceed 10 tons.

(3) *Single vessels greater than 50,000 tons.* Hawser stress for larger vessels is allowed to exceed 10 tons, since these vessels require more mooring lines than either barge flotillas or the smaller single vessels. Model tests indicate that if a lock-filling system is designed to meet guidance (1) and (2) above, hawser stress (extrapolated from the model) will not exceed approximately 25 tons for vessels up to 170,000 dwt.

Existing chamber feature design is based on this guidance; more severe or alternate requirements may require substantially different concepts in hydraulic feature design.

## 2-12. Application

Time saved during lockage is economically significant at most projects and becomes more important when growth of traffic begins to cause prolonged queuing delays. Decreased operation time causes reduced total transit time unless surges and currents in the approaches adversely affect entry and exit conditions. By means of model and prototype tests (see Chapter 6) and design studies, filling-and-emptying systems have been developed that achieve operation times near 8 minutes (min). Both severe decreases and severe increases (unless accomplished by using long valve opening times) in operation time require the development of new systems. For existing systems, operation-time benefit, usually presented as a per minute value, is used to evaluate design modifications that may vary operation time between 8 and 10 min for low-lift and 8 and 12 min for high-lift projects.

*Section IV*  
*Chamber Alternatives*

## 2-13. General

The number and size of chambers are based primarily on capacity studies with system standardization and economics as major constraints (items B6, D6, and U2). Chamber alternatives are briefly discussed in the following paragraphs; guidance and data relating to navigation facility for both single-chamber and multichamber projects are included in EM 1110-2-1611.

## 2-14. Number of Parallel Chambers

In the initial development stage of a waterway transportation system, common practice has been to provide one chamber at each project; then, as traffic has increased, additional chambers have been added. For a new project on a developed waterway, where traffic patterns are well-established and continued growth is assured, two or more chambers may be initially justified on an economic basis. A need for continuous operation may lead to double chambers since, in the event of outage of one lock, essential traffic can be handled on a priority basis. In redevelopment of the Ohio River system, a minimum of two locks have been provided at each of 19 locations.

## 2-15. Chamber Dimensions

Chamber dimensions are influenced by sizes of existing barges and towing equipment; conversely, existing barges and towing equipment have been influenced by sizes of existing chambers. Most of the locks built in the United States since 1950 have usable horizontal dimensions of 84 by 600 ft, 110 by 600 ft, and 110 by 1,200 ft. A number of locks with other sizes have been built: 56 by 400 ft; 75-ft width with lengths varying from 400 to 1,275 ft; 80 by 800 ft; 82 by 450 ft; and 84-ft width with lengths of 400, 720, 800, and 1,200 ft. Recent western

locks (along the Columbia and Snake Rivers) have usable dimensions of 86 by 675 ft. Additional lock chamber length is provided for clearance between the tow and the gates so that gate-to-gate chamber length is greater than usable length. Smaller chambers are used on waterways where the traffic is exclusively recreational boats and small craft.

## 2-16. Chamber Types

The majority of CE lock chambers are for commercial tows with drafts equal to or less than 14 ft, 9 ft being the most common. The design guidance in this manual is derived from studies relating to these chambers. Certain waterways require chambers that are unusual but that provide supplemental operational experience to recent CE lock design, testing, and operational data; these chambers are not evaluated herein. The following listing includes five such chambers.

*a. Ship locks.* Chambers used by oceangoing ships are included in the listing given in Appendix B. Lower sill submergence values for these locks are given in Table 2-2.

*b. Great Lakes shipping.* Commercial vessels are normally individually powered and relatively (for ships) shallow draft. For example, ships with drafts in the range of 16 to 25 ft and sizes from 15,000 to 30,000 dwt are accommodated on the Great Lakes. Lock entry and exit requirements for these types of vessels differ from either barge tow or oceangoing-ship needs (item D3).

*c. Deep drafts.* Chambers designed for both large tows and deep-draft ships (draft 25 ft or greater) need special entry and exit features. Sills are located sufficiently deep to accommodate squat, trim, and sinkage. Towing winches and other assisting mechanisms are used. Ships greater than 100,000 dwt are assisted into the lock chamber. A side-port design has been studied

**Table 2-2**  
**Lower Sill Submergence Values**

<u>Navigation System</u>	<u>Lock Name</u>	<u>Normal Lower Sill Submergence, ft</u>
Gulf Intracoastal Waterway Lake Washington Ship Canal	Inner Harbor	31
	Chittendon (Large)	29
	Chittendon (Small)	16
St. Marys River, South Canal	MacArthur	31
	Poe	32
St. Marys River, North Canal	Davis	23.1
	Sabin	23.1

(item 77) for the New Ship Lock, Mississippi River-Gulf Outlet. These test results are for a 150- by 1,200-ft lock; maximum normal head = 18.4 ft; vessel draft = 45 ft (ships) and 9 and 12 ft (tows). Deep-draft navigation projects are discussed in EM 1110-2-1613.

*d. Recreational locks.* Locks having usable lengths less than 400 ft are listed in Appendix B and are considered recreational locks herein. Limited small-tow and special commercial vessels also use many of these locks. Small locks (and recreational vessels) are discussed in the National Waterway Study (item U2) and published literature (item G4, for example).

*e. Repair facilities.* Dry docks (items A5, B8, and K4, for example) and other similar chambers have mechanical and structural elements comparable to lock chambers. Expeditionary closure and sealing during unwatering are major design requirements.

#### Section V

#### Foundation and Structure Concerns

### 2-17. Hydraulic Loading

The foundation and structural features establish the stability and durability of the structure. Hydraulic loadings during construction, completion, and operation are a major concern. These loadings, because of magnitude and spatial and temporal variations, are complex and require particularly thorough study and interdisciplinary coordination. For example, static conditions at chamber full as compared to chamber empty are recurring changes in loadings that influence deflections and stability parameters for the foundation, walls, and sills of the chamber. Known extreme conditions, such as exist during inspections, in addition to filling or emptying, cause recurring changes in differential-pressure loading across structural elements. Unusual extreme conditions, such as exist during unusual valve and emergency operation, are also of concern. For high-lift locks, the hydraulic design includes high-velocity flow so that passageways may require, for example, special treatment to avoid surface cavitation and abrasion damage. The need for relief of pore pressure within the foundation or within monolith cracks and joints is dependent on hydraulic conditions. These loadings are discussed in EM 1110-2-2602 and other structural presentations (item U1, volume II, for example).

### 2-18. Chamber Structure

Concrete lock structures have been generally reliable and desirable based on engineering and economic considerations. On waterways where traffic is not heavy and at locations on waterways where the lift is very low, sheet-pile locks or possibly earth wall locks have sometimes been used.

*a. Concrete lock structures.* The most common lock structure uses concrete gravity walls founded on either piling or rock (EM 1110-2-2002 and EM 1110-2-2602). Culverts, valve shafts, access passageways, and numerous other special-purpose cavities are contained within the wall. Intakes and outlets may also be formed in the wall although at many locks these are located well outside the actual lock chamber. More unusual concrete lock structures are of the buttress-wall type or have rock walls with anchored concrete facing. For these thin-wall designs, the filling-and-emptying system components are essentially separated from the walls. For the two parallel chambers shown in Figure 2-1, a gravity-wall low-lift design, the intermediate wall serves both chambers. A high-lift lock with concrete gravity walls is shown in Figure 2-2. In Figures 2-3 and 2-4 are high-lift designs with thinner concrete walls anchored to natural rock.

*b. Sheet-pile structures.* Very-low-lift projects permit structures other than concrete to be considered for design; masonry, earth embankment, and sheet-pile structures have been used. Sheet-pile lock walls are of two basic types: sheet-pile cells and M-Z sheet piling supported laterally by wales and tie rods. Sheet-pile locks are filled and emptied by sector gates or other very-low-lift systems. Gate bay monoliths are normally concrete. The low initial cost for sheet-pile structures is offset by short useful life and high maintenance. Recent use has been at sites where temporary (or emergency) locks were needed. A sheet-pile cellular lock is shown in Figure 2-5. Sheet-pile structures are commonly used for cofferdam functions and are discussed in ER 1110-2-8152 and in published literature (items C7 and S10).

*c. Earth embankments.* Earth embankments with concrete gate bays are considered for low-use, very-low-lift projects. For example, these locks are included in the Gulf Intracoastal Waterway to prevent saltwater intrusion and to prevent adverse or dangerous currents during abnormal tide conditions. The walls are essentially

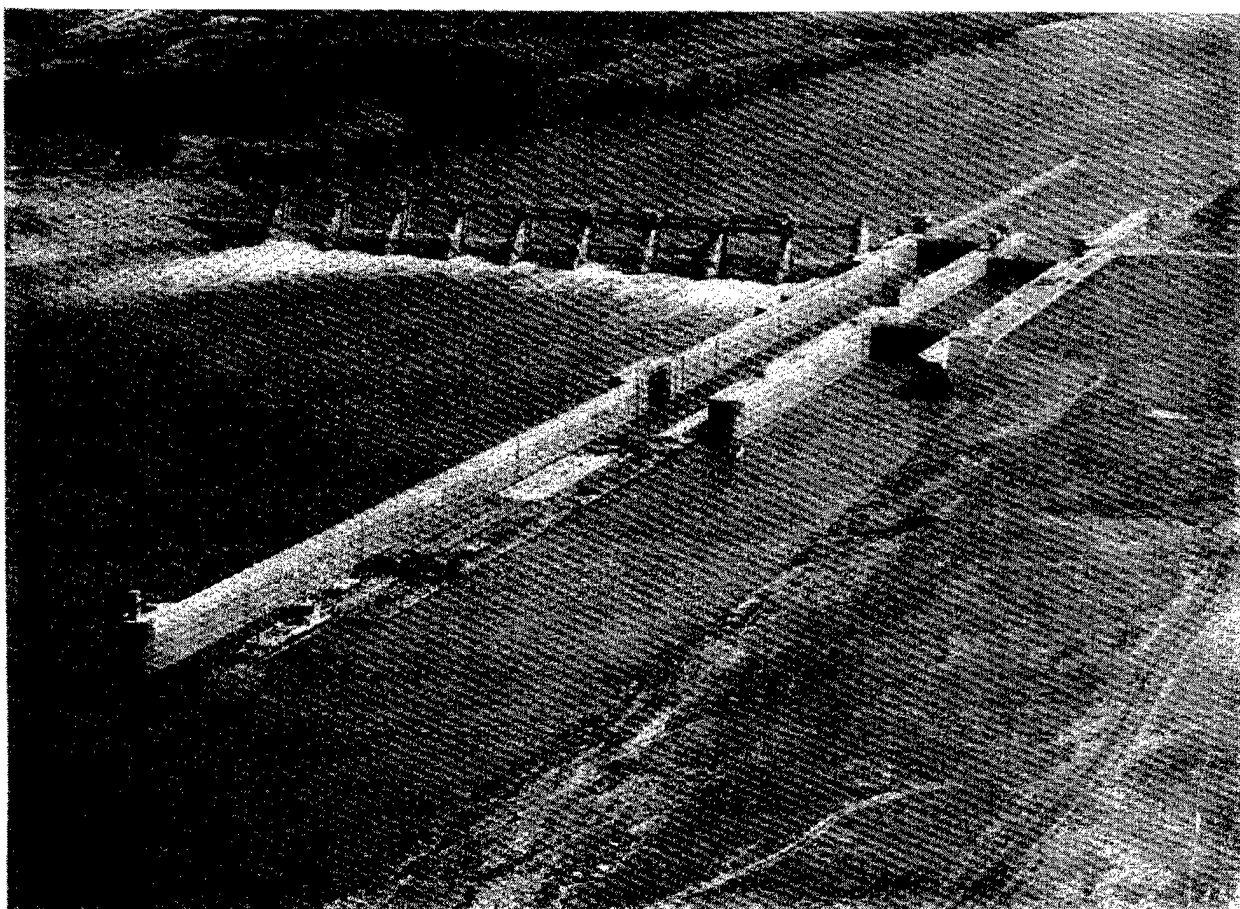


Figure 2-1. Parallel locks with gravity walls. Willow Island Locks, Ohio River, with design lift = 20 ft

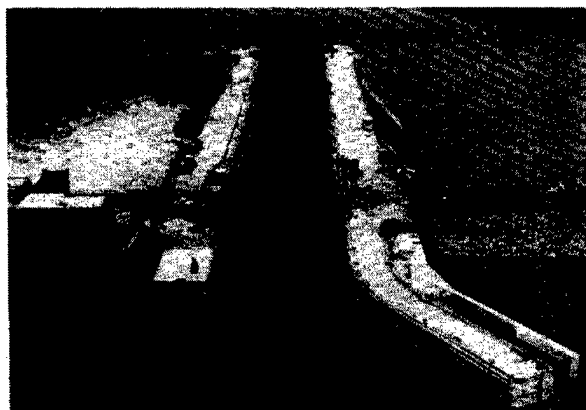


Figure 2-2. Lock with gravity walls. Lower Granite Locks, Snake River, with design lift = 100 ft

levees, with riprap protection on the side slopes. Riprap protects the bottom of the channel (the chamber) from scour due to towboat propellers. Tows moor to timber guide walls during lockage. A lock of this type equipped with sector gates is shown in Figure 2-6. Geotechnical guidance concerning embankment (levees, for example) design is applicable.

#### 2-19. Guide and Guard Walls

Navigation needs (see EM 1110-2-1611 and EM 1110-2-1613) require the proper location and alignment of guide and guard walls and are resolved by means of general river hydraulic models; project purposes in addition to navigation are normally also of concern. These studies, which require preliminary estimates of lockage inflow

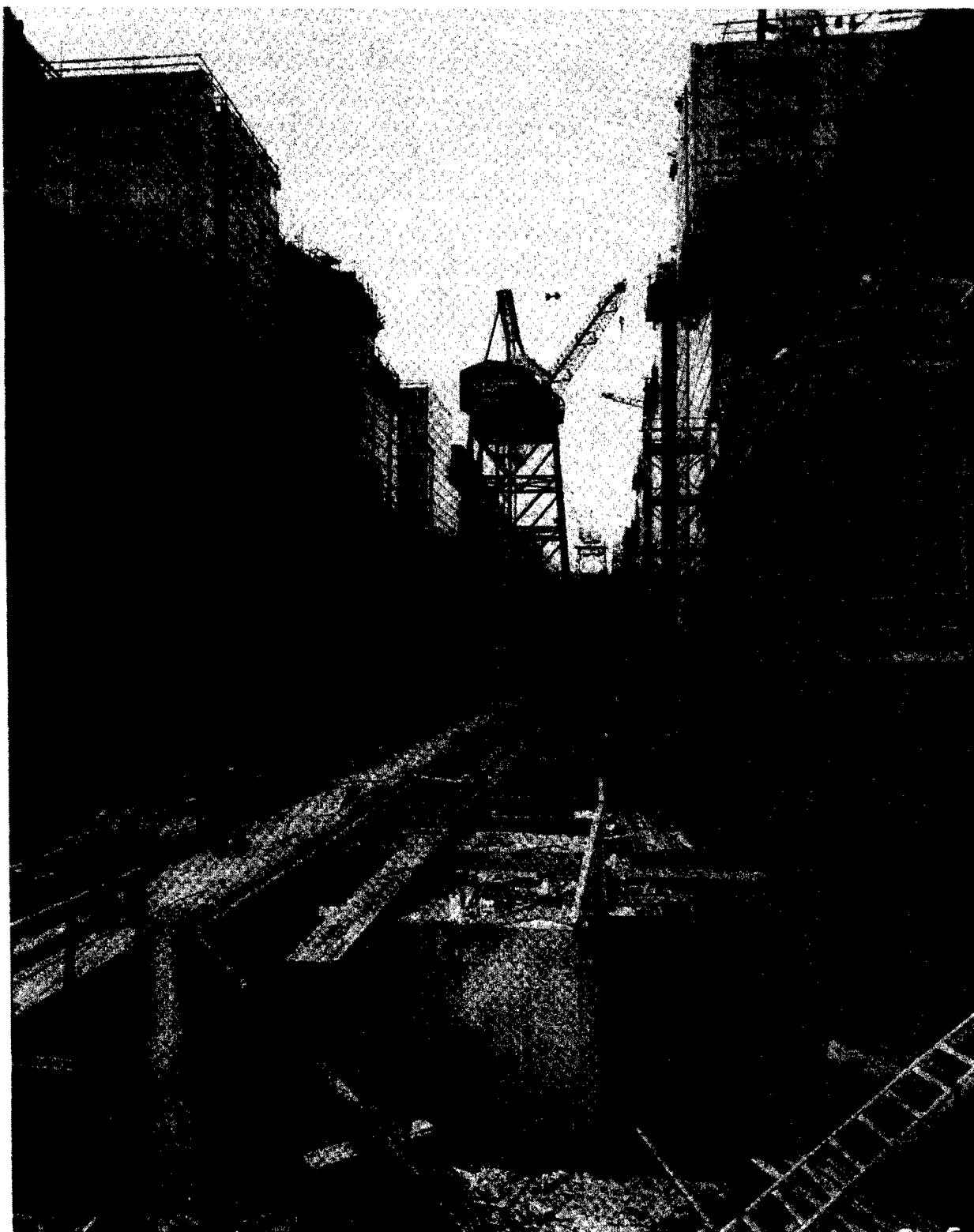
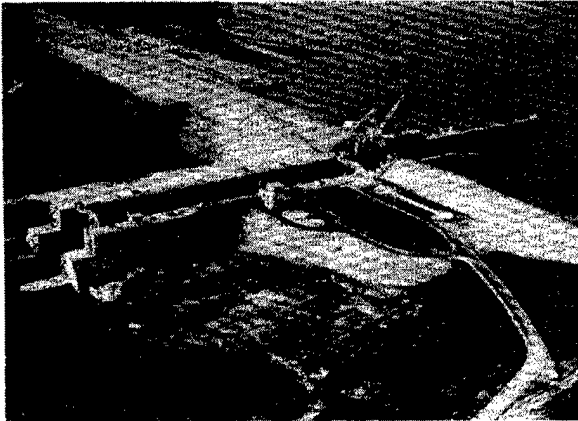


Figure 2-3. Lock with thin walls. The Dalles Lock, Columbia River, with design lift = 88 ft (under construction)



**Figure 2-4. Lock with thin walls. Bay Springs Lock, Tennessee-Tombigbee Waterway, with maximum design lift = 92 ft**

and outflow hydrographs, also determine the impact on navigation regarding type of wall (i.e., floating, ported, or solid). When navigation needs are resolved, then construction and maintenance economics determine the type of wall actually used at a specific project. Similarly, the heights of guide, guard, and lock walls are influenced by

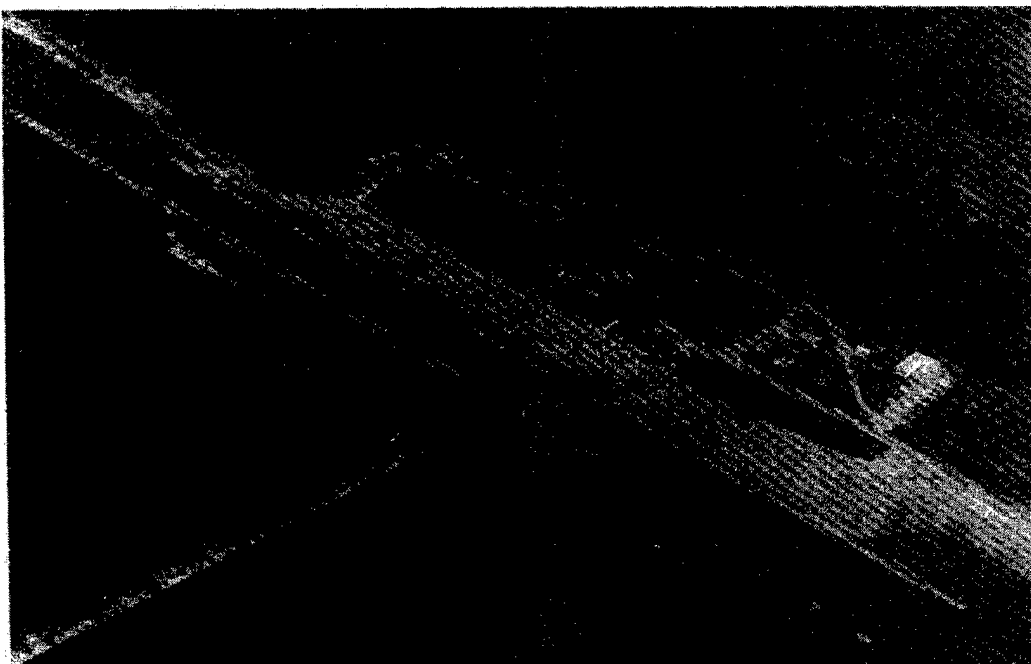
operational as well as navigational needs during high river stages. The following are examples of structural types:

- a. Concrete gravity walls.
- b. Concrete walls supported by structural cellular piling.
- c. Timber walls supported by pile clusters.
- d. Floating moored caisson structures.

Timber structures are normally limited to very-low-lift locks preferably where traffic consists of smaller tows.

## **2-20. Other Structures**

Navigation conditions may require mooring facilities, fleeting areas, and other aides. Examples of structures currently in use are pile dikes (Columbia River, item D11), pile cluster dolphins (item E5), and caissons such as those used for barge docks (item H4). Energy absorption required due to barge impact is a design concern as noted in the reference items; fendering (item R6, for example) structural design guidance is included in EM 1110-2-2703.



**Figure 2-5. Temporary lock with cellular sheet pile. Lock and Dam No. 52, Ohio River, with design lift = 12 ft**



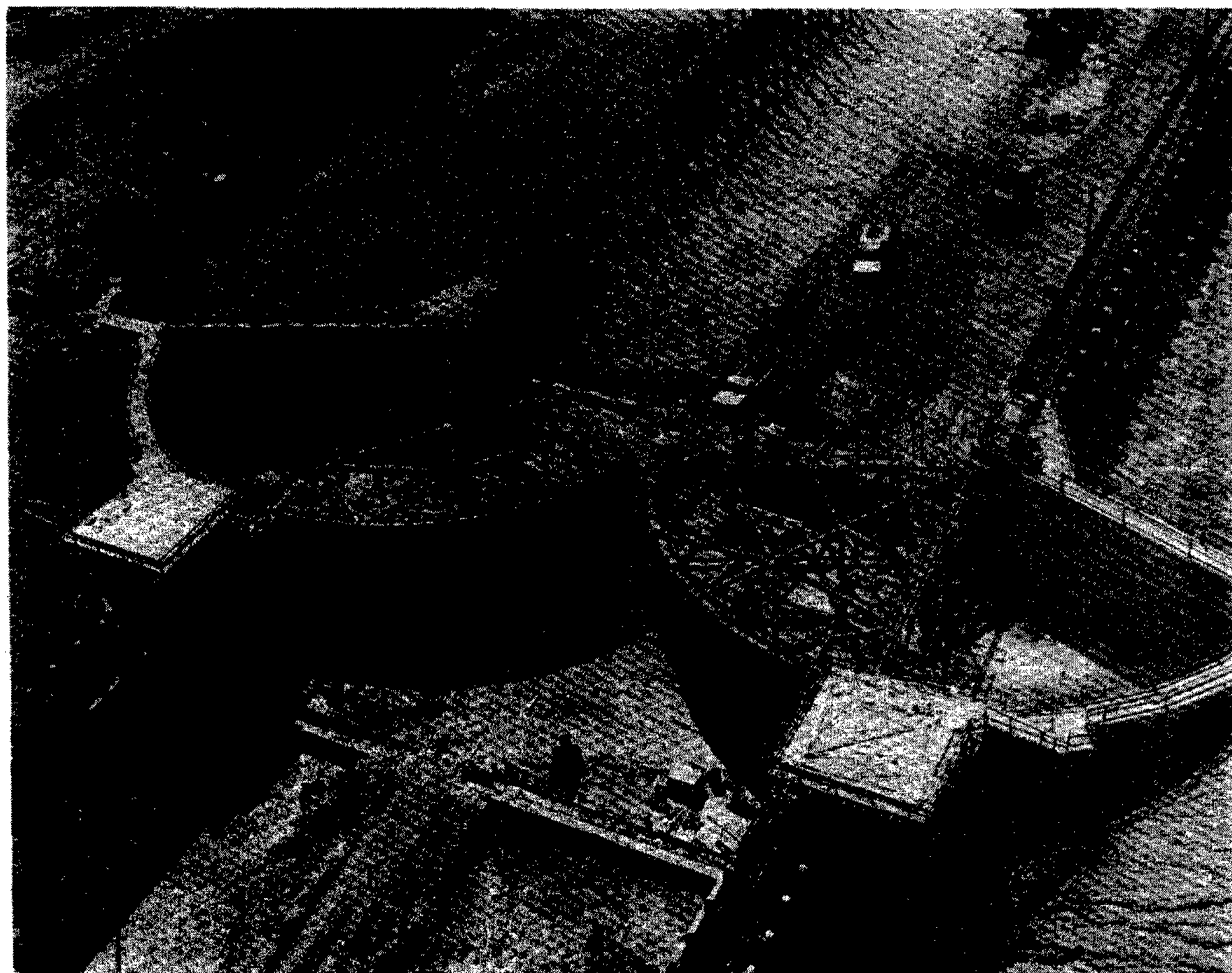


Figure 2-6. Earth embankment with concrete gate bays and sector gates. Vermilion Lock, Gulf Intracoastal Waterway, with design lift = 3 ft (under construction, 1984)

## Chapter 3 Hydraulic Features

### Section I

#### Filling and Emptying

### 3-1. Project Type

Hydraulic design addresses all features relating to filling and emptying the lock chamber. Decisions based on specific authorization requirements (constraints, Table 2-1) narrow hydraulic options.

*a. Maximum navigation lift.* This value determines design type as previously shown in Figure 1-2. For maximum lift near 10 ft, conservative design practice is to use a low-lift rather than a very-low-lift design type. Similarly, for maximum lift near 40 ft, conservative practice is to use a high-lift rather than a low-lift design type. For low-usage locks or for projects with significant variation in lift, economic considerations warrant less conservative design. Lifts greater than 100 ft exceed CE operating experience.

*b. Chamber navigation constraints.* Project identification studies (Chapter 2) identify four constraints relative to chambering:

- (1) Vessel characteristics (types, drafts).
- (2) Clear chamber width.
- (3) Usable chamber length.
- (4) Operation time (economics).

These constraints, compared with existing lock data (Appendix B, item U2, etc.), establish design status compared to CE operating experience. Model- and prototype-tested geometries (see Appendix C and CORPS computer program database H5300) establish status compared to CE verifiable laboratory and field experience. An overview of operating conditions for five specific CE design types is provided in Table 3-1; traffic is different mixes of commercial tows and recreational vessels.

### 3-2. Design Type

The following designations for type of lock filling systems are used throughout this EM.

LC = loop culvert(s)

LCSG = loop culvert(s) and sector gate

SG = sector gates

SP = side ports

SPF = side ports with flume

MP = multiport system

BL1 = centered lateral-manifolds; one culvert

BL2 = centered lateral-manifolds; two culverts

BLC = centered lateral-manifolds; high-lift modified

SBLC = split lateral-manifolds

OC = longitudinal centered and ported culvert

HB4 = horizontal flow divider; 4 longitudinal manifolds

HB8 = horizontal flow divider; 8 longitudinal manifolds

VB4 = vertical flow divider; 4 longitudinal manifolds

VB8 = vertical flow divider; 8 longitudinal manifolds

New projects are compared in terms of lift, chamber geometry, and navigation constraints with existing designs listed in Table 3-1; however, site-specific conditions may require a different design. For each lift category, the design type is judged as matching, modified, or new as follows.

*a. Very-low-lifts (0-10 ft).* For matching *sector gate* (SG) designs, sill and floor elevations and gate operation schedules are from specific model-tested designs (Appendix C). Modified designs to accommodate small chamber-dimension changes (when geometric similarity is essentially retained) can be reliably determined from existing designs. New designs (due to unusual or more stringent navigation constraints, untested end-filling devices, or major changes in chamber dimensions) require laboratory testing and evaluation to determine chamber performance. Low-lift design types (*b* below) are conservative alternatives for very-low-lift projects.

*b. Low-lifts (10-30/40 ft).* For matching or modified *side-port* (SP) designs, sill and floor elevations and valve schedules are from design criteria (see Appendix D). For two-culvert projects the choice of lateral culverts (BL2) as compared to side ports has been an economic consideration (structural cost, chamber maintenance, and excavation costs are major factors); the side-port system is least-cost for the ongoing Gallipolis new main lock (110 by 1,200 ft, 23-ft normal lift). Unfortunately,

**Table 3-1**  
**Experience with Recommended Designs (Geometries Constructed Since 1950)**

Type	No. of Similar Locks	Chamber	
		Clear Width ft	Usable Length ft
Very-Low-Lift Designs (Maximum Lift <sup>a</sup> < 10 ft)			
Sector gate (SG)	1	86	600
	1	84	600
	1	75	1200
	1	75	1150
	1	75	800
	1	56	800
	1	45	800
	7	30	90
	7	30	90
Temporary (SPF)	<u>2</u>	110	1200
Total	<u>23</u>		
Low-Lift Designs (Maximum Lift <sup>b</sup> < 30/40 ft)			
Side port (SP)	10	110	1200
	67	110	600
	10	84	600
	22	56	360
Laterals (BL2)	7	110	1200
	6	110	600
	2	84	720
Laterals (BL1)	7	110	600
Total	<u>131</u>		
High-Lift Designs (Maximum Lift > 40 ft); Longitudinal Manifolds			
4-manifold (HB4)	2	110	600
8-manifold (HB8)	1 <sup>c</sup>	86	675
Total	<u>3</u>		

**Notes:**

<sup>a</sup> Lifts greater than 10 ft are experienced at many of these projects.

<sup>b</sup> Lift experienced during actual operations extends up to about 37 ft; commercial traffic is primarily 9-ft-draft tows.

<sup>c</sup> Lower Granite Lock became operational in 1975; tows up to 14-ft draft use this project.

existing BL2 designs have unfavorable single-culvert operating characteristics which tend to preclude their use for new projects (paragraph 3-3). For one-culvert

projects (auxiliary or alternative locks) a lateral design (BL1) is used. Because of the broad extent of testing and experience with these types of locks, a need for a new design is considered unlikely. However, were a site-specific situation to require more rigid requirements on chamber performance or to require alternate culvert geometries (due to an unusual site-specific constraint, for example) then an alternative design could be justified. The alternate design would probably be similar in concept to the existing high-lift designs and would require extensive laboratory testing and evaluation to determine chamber performance (item 74, for example).

*c. High-lifts (30/40-100 ft).* For matching balanced flow designs for both four manifolds (HB4) and eight manifolds (HB8), sill and floor elevations and valve schedules are from design criteria (see Appendix E). Matching designs must agree in detail; that is, in addition to chamber dimensions, ports, baffles, sills, etc., are to be sized and shaped according to either HB4 or HB8 existing details. The complete culvert-to-chamber (cross-over culvert) system must also match in geometric detail. Any change constitutes a modified design which, as for a new high-lift design, requires laboratory testing and evaluation in terms of chamber performance and of reliability and durability of the total design.

### 3-3. Lateral Culverts

Concepts similar to the BL2 design have been tested and are in operation at numerous projects. Unlike side-port designs, inconsistency in geometric detail for lateral-culvert designs (note BLC, BL1, BL2, and SBLC in Appendix B, Table B-1) precludes the development of broad design criteria. The following factors have caused lateral culverts (including the BL2 design) to be viewed as less acceptable than side-port systems (for low-lift) or longitudinal systems (for high-lift).

*a. Slow valving.* Four-minute or greater valve times have been used extensively; rapid operation requires more rapid valving.

*b. Rigid valve times.* The valve time established during testing (*a* above) cannot be reduced without a significant deterioration in chamber performance.

*c. Harmonic oscillations.* Natural oscillations of the chamber water surface appear (item 71) to be excessively stimulated, leading to large hawser forces.

*d. Synchronous valving.* Any valving other than two-valve fully synchronized valving causes chamber

performance to severely deteriorate in terms of oscillations (*c* above) and free tow movement.

### 3-4. Features

The design considers each of the following six compatible systems.

*a. Intake system.* Conditions in the upper approach channel are concurrently resolved by hydraulic design, navigation facility and safety, operations, and other multipurpose or multidiscipline concerns. Guide and guard walls are specific items of major concern to navigation. Intake manifold, trash rack, and transition conduit are hydraulic design features.

*b. Filling valve system.* Valve design is a hydraulic concern as are the valve well, bulkheads, air vent, and flow-passage designs. Hydraulic loadings required for structural and mechanical detail design are required in addition to flow parameters needed solely for lock filling and emptying.

*c. Culvert-to-chamber system.* The culvert, manifold(s), ports, and transitions are hydraulic design features. Chamber navigation conditions (expressed as turbulence, hawser stress, and vessel drift) are highly influenced by culvert-to-chamber geometry.

*d. Chamber system.* Features making up the lock chamber, such as the upper and lower gates and

navigation and operation aids, are concurrently resolved by hydraulic design, navigation facility and safety, operations, and other design functions. The lock sill and chamber floor elevations, manifold recesses, and baffles are hydraulic features.

*e. Emptying valve system.* The listing of features is the same as for the filling valve (see *b* above).

*f. Outlet system.* Conditions within the lower approach channel are, as for the upper approach, multipurpose and multidiscipline concerns. The transition conduit and outlet manifold and baffles and energy dissipator are hydraulic design features.

The features within each system are modified during design for each site-specific lock. The systems for each basic design type (very-low-lift, low-lift, and high-lift locks) are distinctly different; and within each design type, certain features are varied when necessary to resolve project constraints.

### 3-5. Recent Designs

Projects of each of the seven design types listed in Table 3-1 have recently been designed. Each of the types and the corresponding feature locations (paragraph 3-4) are shown in Plates 3-1 through 3-8 as summarized in Table 3-2.

**Table 3-2**  
**Design Types and Example Project Locations**

Plate No.	Design Type Symbol	Design Type	Project Lock	Key Reference Studies Item, Appendix A
3-1	SG	Sector Gate	Vermilion; Gulf Intracoastal Waterway	20: WES TM 2-309 36: WES TR 2-556
3-3	SP	Side Port	Willow Island Main Lock; Ohio River	51: WES TR 2-678 57: WES TR 2-713
3-4	SP	Side Port	Ozark; Arkansas River	61: WES TR 2-743 72: WES MP H-75-7
3-5	BL2	Bottom Lateral (2 culverts)	Belleville Main Lock; Ohio River	46: STP No. 66 43: STP No. 74
3-6	BL1	Bottom Lateral (1 culvert)	Willow Island Auxiliary; Ohio River	17: STP No. 52 23: STP No. 59
3-7	VB4	Vertically Split Balanced Flow (4 Manifolds)	Bay Springs; Tenn-Tombigbee Waterway	78: WES TR H-78-19
3-8	VB8	Vertically Split Balanced Flow (8 manifolds)	Lower Granite; Snake River	79: BHL TR No. 126-1

*Section II**Appurtenant Concerns***3-6. General**

Constraints, such as those listed previously in Table 2-1, result in design features that are resolved concurrently with the design of the basic filling-and-emptying system. Constraints and resulting features vary on a project-to-project basis; specific needs leading to common appurtenant concerns are described in the following paragraphs with design detail for major items included in Chapter 7.

**3-7. Navigation Aids**

These devices are recessed into the lock wall, flush-mounted on the wall face, or located on the upper surface of the wall. The objective is to provide assistance to navigation (for all anticipated vessel types) commensurate with clear chamber width and minimum maintenance. Examples are floating mooring bitts, ladders, line hooks, check posts, ring bolts, and staff gages.

**3-8. Surge Reduction**

Currents and water-surface elevations in the upper and lower approaches to the chamber are major concerns to navigation. For canals and smaller waterways these surge effects, during both filling-and-emptying, are severe constraints to hydraulic design (EM 1110-2-1606). Coordination involving both navigation (EM 1110-2-1611) and hydraulic studies is needed in order to determine locations of intakes and outlets, alignment and types of guide and guard walls, and geometries of the approach canals such that surge effects are acceptable to navigation. In the event that these effects cannot be resolved at acceptable costs, then the hydraulic filling or emptying operation times may be extended either by valving or by using a less efficient hydraulic system. Alternatives to slowing the systems, such as using storage basins (surge reduction basins) adjacent to intakes or outlets, are noted in Chapter 5.

**3-9. Impact Barriers**

Protection of the upper or lower gates from collision by navigation vessels is the primary objective. Wood, rubber, and metal fenders and bumpers are used on gates, on key locations along guide and guard walls, and on the exposed surfaces of the recessed gates as inexpensive and repairable energy absorbers. Protective equipment is discussed in EM 1110-2-2602.

**3-10. Water Saving**

Environmental or economic factors may require design features directed toward minimizing the quantity of water transferred during lockage. The problem is addressed at three stages in project life:

a. Preliminary studies for the selection of number of chambers and chamber sizes may result in including either a small hydraulic lock or a mechanical lift for smaller (normally recreational) vessels.

b. During design, consideration of either adding an extra set of lower gates (to permit fractional chamber operation) or including a water-saving chamber (to permit saving a fraction of the water normally lost during emptying for use during filling) may be warranted. Neither has been feasible for CE locks. Staged-lifts (item 07) normally use less water than single-lift locks at an expense in operating costs and transit time.

c. During operation, lockage procedures directed toward reducing the number of operations required for passing a mix of vessel sizes result in water-savings benefits.

**3-11. Dewatering**

Maintenance is the primary objective. Scheduled inspections require full and partial dewatering of the lock chamber and most flow passages. Provisions to facilitate pumping for elevations below lower pool should be provided. Closure is during static conditions and is normally accomplished by means of bulkheads. Canal bulkheads above and below the upper and lower, respectively, chamber gates are used to isolate the chamber gates. Culvert bulkheads above and below each valve are used to isolate the culvert valves. Hydraulic design emphasis, particularly for high-lift locks, is to shape and locate the culvert bulkhead slots for minimum disturbance to the flow with no cavitation at the boundary while satisfying sealing and structural requirements during closure.

**3-12. Emergency Closure**

Risk associated with failure of the upper miter gates may justify the installation of devices for closure of the chamber during free-surface flow directly over the upper sill. Various closure devices are available as described in EM 1110-2-2703 and EM 1110-2-2602. For a highly developed waterway, such as areas along the middle reaches of the Ohio River, significant monetary losses

and other hazards could result from unrestricted flow. The three principal sources of loss are:

- a.* Loss of pool upstream from the lock.
- b.* Possible flood damage downstream from the lock.
- c.* Loss to shipping, recreation, and other project purposes on both pools, particularly in the upstream pool.

The high-lift locks and dams along the Columbia and Snake Rivers in Washington and Oregon provide a contrast to the Ohio River emergency situation. These dams create relatively large deep reservoirs that are used to produce hydropower. Free flow through a lock at one of these projects does not constitute a major portion of the total riverflow and the loss of reservoir storage results primarily in a loss of power production.

### **3-13. Debris Control**

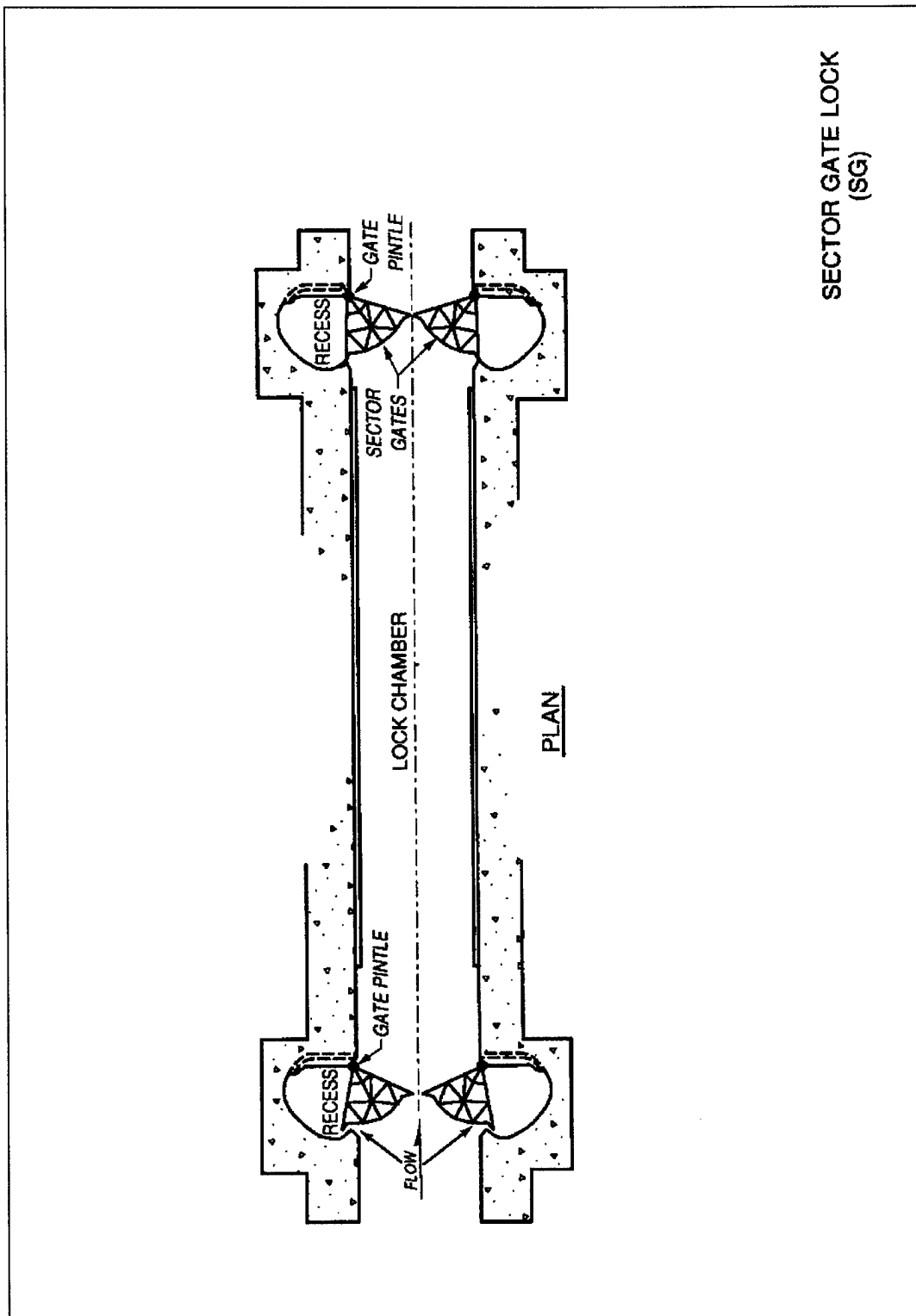
Material that drifts along waterways includes sediment, damaged barges, timber, ice floes, etc. Chamber siting and guide and guard wall design (see EM 1110-2-1611) influence the extent to which waterway debris tends to enter the upper approach. These materials are of concern to navigation; valve, gate, and flow passage operation; and general maintenance of chamber and approaches.

Primary hydraulic concerns are:

- a.* Flow patterns and operational procedures directed toward flushing surface (floating) material over the upper sill, through the lock chamber, and out of the lower approach.
- b.* Trash bars and trashracks at culvert intakes designed for exclusion of submerged materials from the filling-and-emptying system.
- c.* Selection and design of the gates (see EM 1110-2-2703) and sills for reliable operation in the presence of both surface and submerged debris and for maintenance removal of unusual materials.
- d.* Identification of locations along the flow passage boundaries and the chamber floor at which long-term accumulations, physical damage, and other major inspection and maintenance concerns exist.

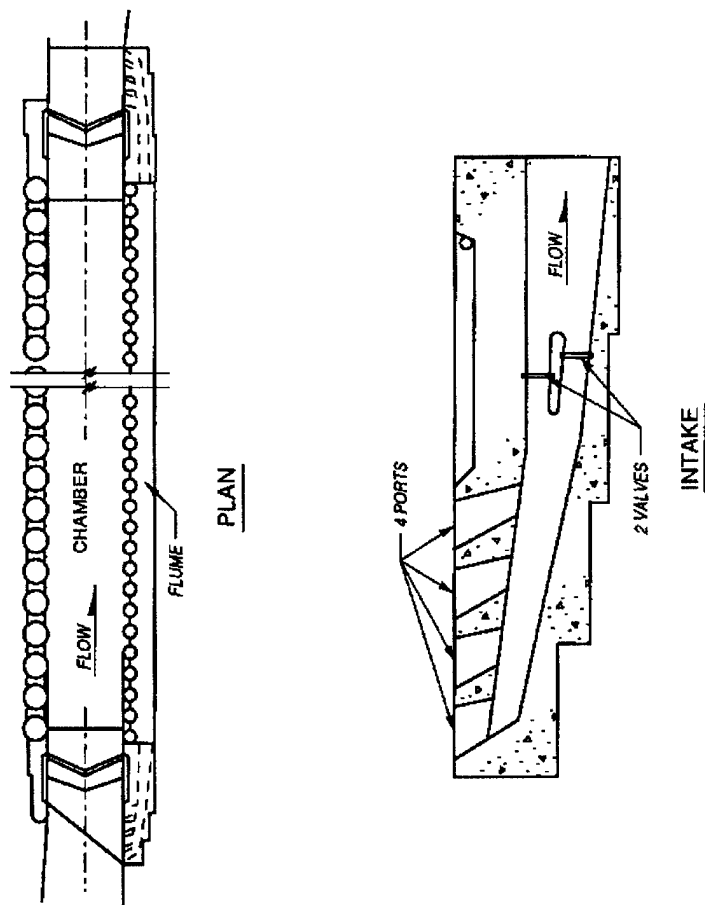
### **3-14. Ice Control**

Recent interest in year-round navigation has led to specialized studies of winter lockage problems. The interest is directed toward navigation problems in general and includes lock design and maintenance techniques. These are reviewed in Chapter 7 and specific guidance is included in EM 1110-2-1612.



SECTOR GATE LOCK  
(SG)

Plate 3-1



SIDE-PORT/FLUME  
TEMPORARY LOCK  
(SPF)

Plate 3-2



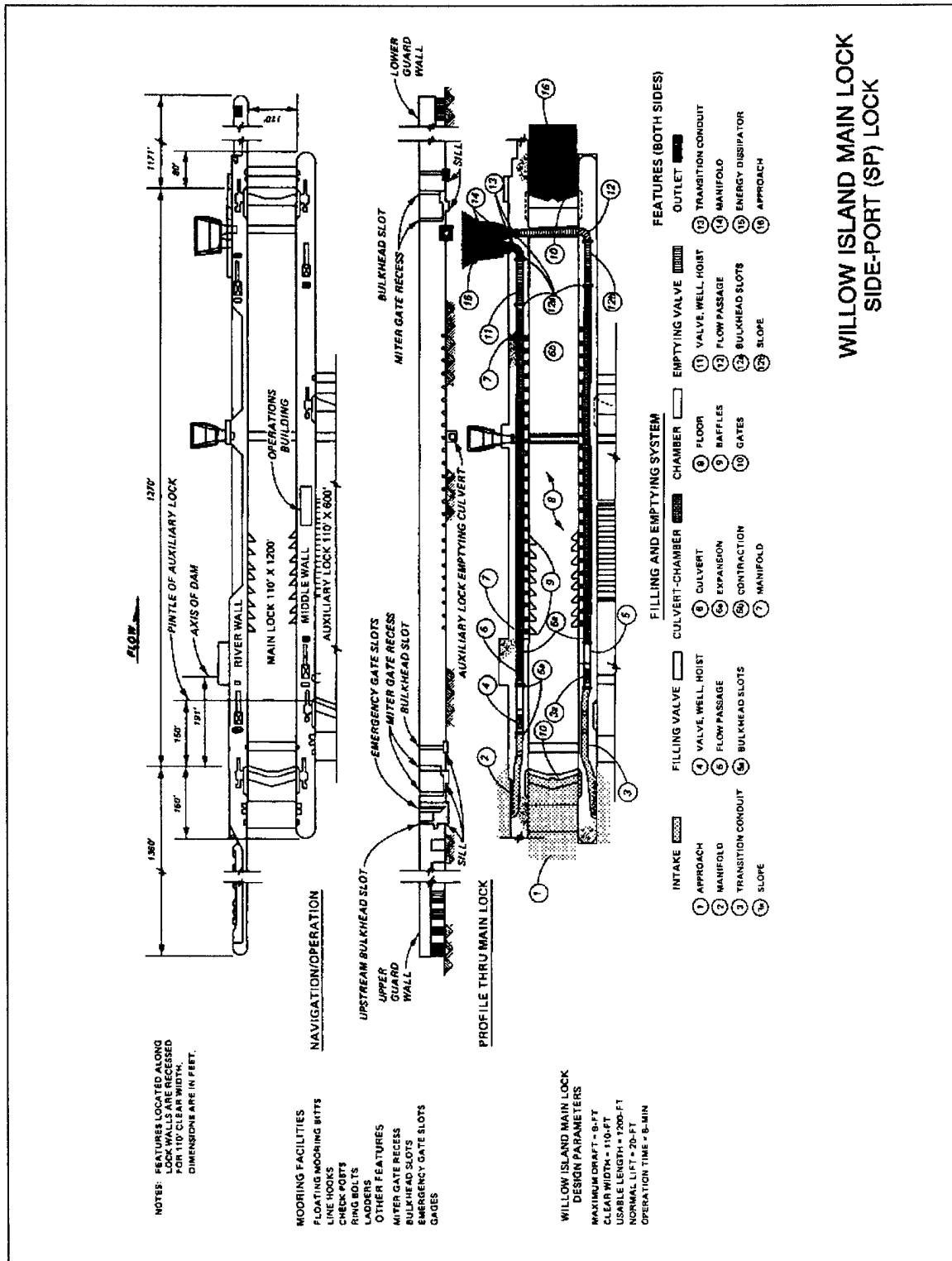


Plate 3-3

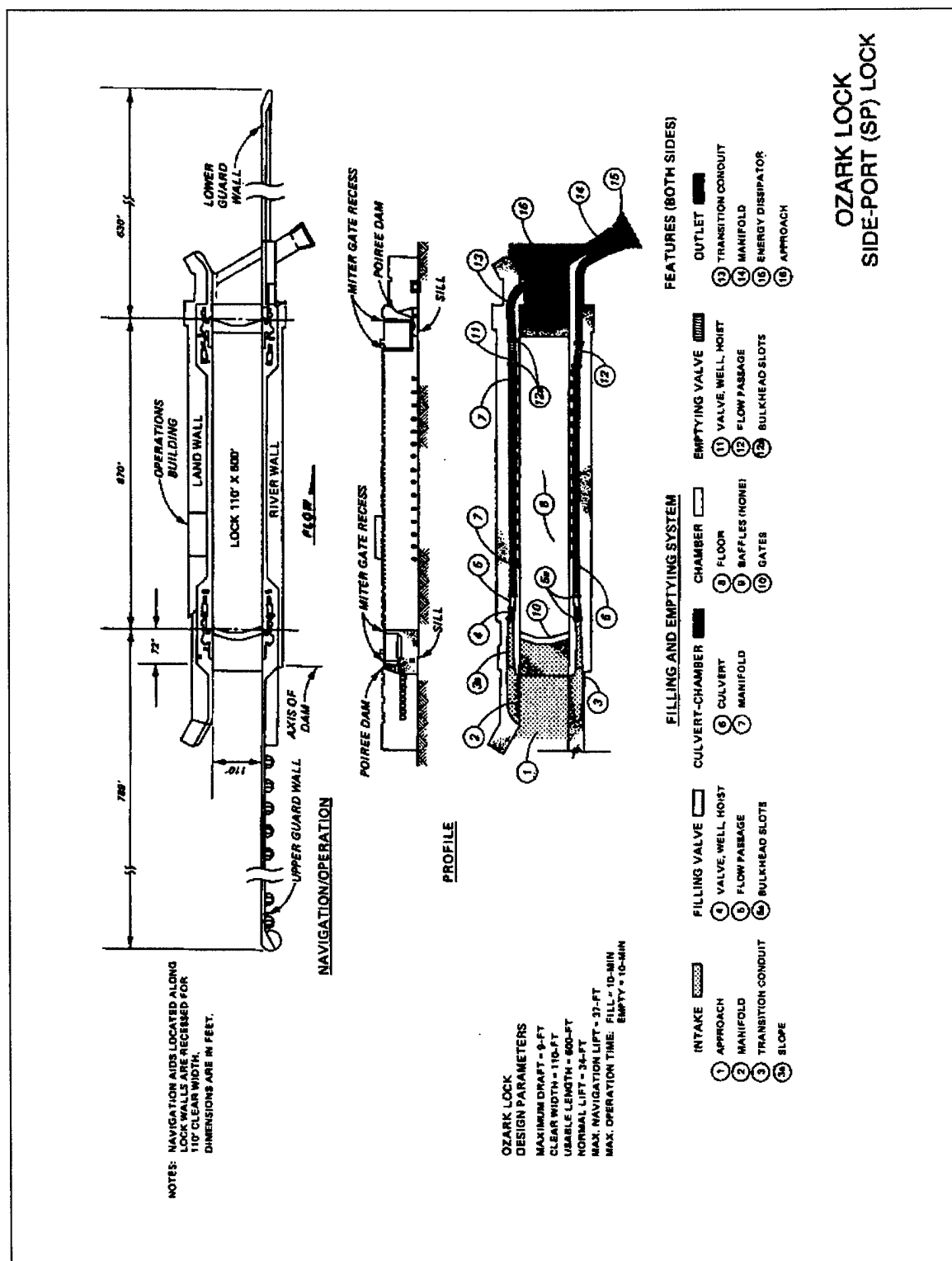
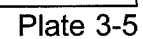


Plate 3-4



**NOTE:** NAVIGATION AIDS LOCATED ALONG CHANNEL ARE PRECISED FOR 100-FT CLEAR WIDTH. DIMENSIONS ARE IN FEET.

**WILLOW ISLAND AUXILIARY LOCK**  
DESIGN PARAMETERS

MAXIMUM DRAFT - 8 FT  
CHANNEL WIDTH - 100 FT  
CHANNEL DEPTH - 800 FT  
MINIMUM LIFT - 70 FT  
OPERATION TIME - 8 MIN

**PROFILE THRU AUXILIARY LOCK**

UPPER GUIDE WALL  
UPSTREAM BULKHEAD SLOT  
NAVIGATION/OPERATIONS  
AUXILIARY LOCK 110' X 800'  
MAIN LOCK 110' X 1200'  
OPERATIONS BUILDING  
LOWER GUIDE WALL  
UPSTREAM BULKHEAD SLOT  
WATER GATE RECESS  
BULKHEAD SLOT  
WATER GATE RECESS  
BULKHEAD SLOT  
CHAMBER FLOORS AND MAIN LOCK  
CULVERTS ARE OVER FLOW PASSAGE

**WILLOW ISLAND AUXILIARY LOCK**

MAXIMUM DRAFT - 8 FT  
CHANNEL WIDTH - 100 FT  
CHANNEL DEPTH - 800 FT  
MINIMUM LIFT - 70 FT  
OPERATION TIME - 8 MIN

**FEATURES (ONE SIDE)**

**FILLING AND EMPTYING SYSTEM**

**INTAKE** (1) APPROACH (2) MANIFOLD (3) TRANSITION CONDUIT (4) SLOPE

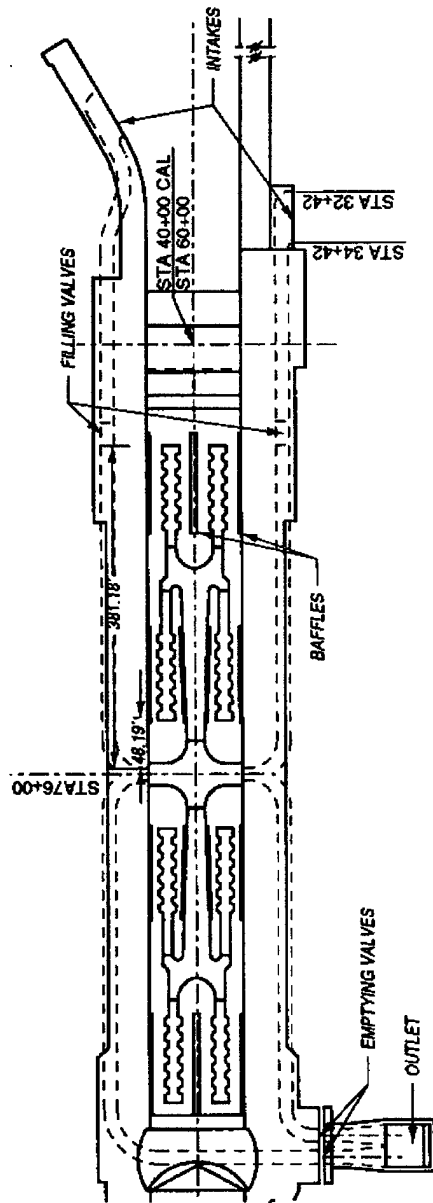
**FILLING VALVE** (5) VALVE, WELL, HOIST (6) FLOW PASSAGE (7) BULKHEAD SLOTS

**CULVERT-CHAMBER** (8) CULVERT (9) MANIFOLD (10) LIGHT LATERALS (11) BULKHEAD SLOTS

**EMPTYING VALVE** (12) VALVE, WELL, HOIST (13) FLOW PASSAGE (14) BULKHEAD SLOTS (15) SLOPE

**OUTLET** (16) TRANSITION CONDUIT (17) MANIFOLD (18) ONE PORT (19) ENERGY DISSIPATOR (20) APPROACH





LOWER GRANITE  
HORIZONTAL FLOW DIVIDERS  
8-MANIFOLD (HB8) LOCK

Plate 3-8



Spillway tainter gate structural details are suggested as appropriate for tainter gates on lock sills (EM 1110-2-2703).

*d. Other gates.* Navigation inconvenience at lower pool (rising single-leaf vertical lift gates) and clearance for opening at upper pool (submersible or rising single- or double-leaf vertical lift gates) preclude a significant reduction in sill spacing by using narrower gates. Gate designs are discussed briefly in Appendix B and detailed in EM 1110-2-2703. Lock chambers using gates other than miter gates are unusual in CE design practice.

### 4-3. Sill Spacing

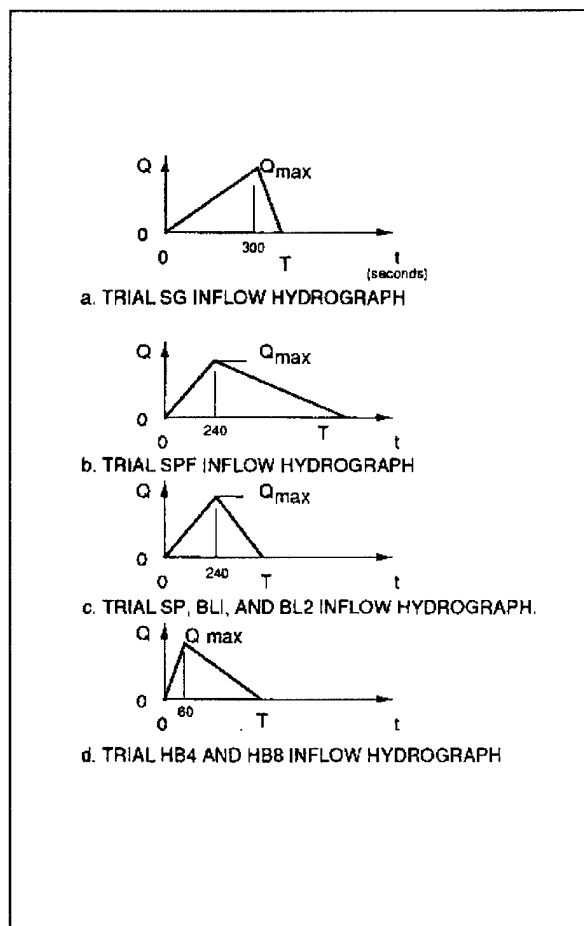
For preliminary layouts, sill spacing is based on usable length and miter gate or sector gate leaf extension; approximately 10 ft is added to provide a combined sill and gate clearance. Final gate selection considers structural, mechanical, and economic factors in addition to hydraulics and may result in an alternate gate and a small change in sill location.

### 4-4. Location of Intake Structures

The chamber inflow hydrograph (flow rate,  $Q$ , as a function of time,  $t$ ) is finalized during hydraulic feature design; however, estimates of flow are required before these details are known. Intake structures are located so that lockage flows are a minimum liability to navigation and also satisfy other site-specific constraints. Navigation conditions are often determined by means of small-scale hydraulics models (see EM 1110-2-1611 and item F4, for example) which require preliminary estimates of lock inflow rate.

### 4-5. Lock Filling

CORPS program H5320 or other expedient calculation (item R1, for example) is used to provide  $Q$  as a function of  $t$  for the lift and geometry of the new lock. Should operation time ( $T$ , Chapter 5) be greater than authorized, then system size is increased; additional costs as compared to the existing lock are anticipated. Should operation time be less than authorized, then system size may be decreased. Idealized hydrographs, as shown in Figure 4-2, may also be used to establish preliminary estimates of lock inflow. The volume of inflow, using a discharge  $Q$  as a function of time  $t$ , is set equal to the change in lock chamber water volume. The following guidelines identify rapid filling times (small  $T$  values) for existing designs.



**Figure 4-2. Idealized lock filling hydrographs for preliminary estimates of lock inflow**

*a. Very-low-lift designs.* For SG locks, the gate opening rate and pattern are adjusted in the prototype to accommodate various lift, vessel, and approach conditions. For SPF locks, valve pattern and port openings are adjusted in the prototype for the same reasons. Operation times near 10 min (items B9, P2) are the minimum achievable for acceptable chamber performance. For small SG chambers with recreational traffic, lower lifts, and adequate submergence, an operation time nearer 5 min may be appropriate.

*b. Low-lift designs.* For SP locks, acceptable chamber performance is obtained during hydraulic feature design for a specific filling time and specific commercial traffic (9-ft-draft tows) because of tested relationships between lift, chamber dimensions, submergence, port dimensions, baffles, and valving. An 8-min operation time is a common goal for lifts near midrange, 25 ft. Predesign estimates of SP operation time for an 84-by



600-ft chamber and 4-min valving are shown in Figure 4-3. Neither BL2 nor BL1 designs have as comprehensive a set of operation time versus submergence data as do side-port systems. For these systems, a filling time  $T$  of 8 min and a valve time  $t_v$  of 4 min are suggested for preliminary inflow estimates for the entire low-lift range.

*c. High-lift designs.* HB4 and HB8 chamber details are variable during design only with extensive laboratory testing regarding chamber performance. Both systems are designed for rapid valving ( $t_v = 1$  min) and rapid filling. Prototype filling times for these systems are estimated in Figure 4-3 for lifts ranging from 40 to 100 ft. Making these systems slower, except by valving, or faster requires significant changes of chamber features.

#### 4-6. Chamber Depth

Chamber depth  $D_c$  (Figure 4-4) for design purposes is the depth of water in the lock during navigation lockage conditions. The minimum depth corresponds to the minimum tailwater elevation and the maximum depth to the maximum upper pool elevation for which lockage is planned. The choice of the chamber floor elevation must include safety and economic considerations. The time of entry and the filling/emptying time are decreased while the cost of the structure is increased as the chamber depth is increased. Safety is improved as the chamber depth is increased. The minimum chamber depth must have a filling time that is slow enough not to violate the 5-ton hawser stress guidance. Figure 4-3 is an example. It may be that the sill depth requirements (paragraph 4-7) will limit the minimum chamber depth. An economic analysis using the incremental delays in lock transits for increments of tailwater/headwater durations versus the incremental structural cost of providing various chamber depths is employed to optimize the benefit to cost ratio. Project experience is listed in Table 4-2 and discussed in the following paragraphs. Submergence is defined as the difference in elevation between lower pool and chamber floor. Cushion is defined as the elevation difference between vessel keel and chamber floor for zero velocity conditions.

*a. Very-low-lift designs (0-10 ft).* These locks have been constructed with chamber floor at navigation channel bed elevation. The submergence has therefore been established by upstream and downstream channel conditions rather than chamber performance.

*b. Low-lift designs (10-30/40 ft).* The minimum submergence for optimum filling/emptying time for

side-port locks is the tow draft plus one-half the side-port spacing (item 72). For a 9-ft-draft tow in a 110-ft-wide lock, the optimum minimum submergence is  $14 + 9 = 23$  ft. When excavation costs associated with deep submergence are significant, then the lateral BL2 system has been used. Using 16-ft submergence plus 7-ft lateral-culvert total height = 23 ft as criterion, then for lifts less than about 25 ft, BL2 is not an economical alternative to SP systems. For lifts above 25 ft, the BL2 design has been used instead of the SP design provided reduced excavation represents a major economic factor as compared to the expense of lateral culverts and risk during single or nonsynchronous culvert operation is operationally acceptable. The high-lift HB4 type of design is expected to be an effective alternative to BL2 designs, although use in 1,200-ft chambers has yet to be studied. The auxiliary lock, BL1, is normally set so that submergence is equal to that of the main lock.

*c. High-lift designs (30/40-100 ft).* Submergence values are as shown in Table 4-2 for the listed lifts. The extreme excavation measured from lower pool to the lowest invert in the crossover area is 34 ft for HB4 design and 41 ft for HB8 design. The HB8 design with modified crossover culverts has been model-tested for a 69.5-ft lift, 14-ft-draft tows, 5-ft cushion, and 86-ft by 675-ft chamber with no evidence of unsatisfactory performance. The VB4 designs, which have similar manifolds but modified crossovers as compared to HB4, have been model-tested for lifts ranging from 30 to 100 ft for a range of lifts and chamber sizes; prototype experience (see Appendix B) is available with these designs. The HB4 design (modified) was considered for a 130-ft lift, 84- by 600-ft chamber; however, the project was terminated for economic rather than operational reasons.

#### 4-7. Sill Elevation

Sill depth  $D_s$  (Figure 4-4) for design purposes is the depth of water over the sill during navigation lockage conditions. The minimum depth corresponds to the minimum tailwater elevation for the lower sill and to the minimum upper pool elevation for the upper sill.

#### 4-8. Sill Elevation Guidance

The choice of sill depth must include safety and economic considerations. As the sill depth is either the same or less than the chamber depth, it becomes the governing factor for safety and tow entrance time. A sill depth less than 1.5 times the tow draft (1.5d), except for very-low-lift (0-10 ft) locks, should not be considered

**Table 4-2**  
**Submergence Values**

Design Type	Project (see Appendix B)					Traffic		Submergence <sup>b</sup> ft	Cushion <sup>c</sup> ft
	Name	Data <sup>a</sup>	Length ft	Width ft	Lift ft	Type	Draft ft		
Very-Low-Lift Projects									
SG	Vermilion	D	110	1,200	5	Tow	9	15	6 [3]
SG	W. G. Stone	D	86	640		Rec.	12	15	3 [0]
SG	Algiers	M	75	800	8	Tow	14	15	1
SG	S-61	D	30	120	Rec.	Tow	9	13.6	4.5
SPF	L&D 52	D	110	1,200	12	NV <sup>d</sup>	7.5	NV <sup>d</sup>	
						Tow	9	12.0	3
Low-Lift Designs									
SP	Willows Is. Main	D	110	1,200	20	Tow	9	25	16
SP	Ozark	D	110	600	34	Tow	9	27	18
BL2	Belleville Main	D	110	1,200	22	Tow	9	28	19
BL2	Markland	M	110	1,200	3	Tow	9	16.5	7.5
BL2	Greenup	M	110	1,200	30	Tow	9	16	7
BL1	Willow Is. Aux.	D	110	600	20	Tow	9	25	16
High-Lift Designs									
VB4	Bay Springs	M	110	600	92	Tow	9	15	6
VB6	Lower Granite	M	86	675	105	Tow	9	17	8

**Notes:**

- <sup>a</sup> M = model tested for satisfactory chamber performance; D = design normal values. Listing includes projects shown in Plates 3-1 through 3-8.  
<sup>b</sup> Submergence is lower pool elevation minus chamber floor elevation; values in brackets are minimums.  
<sup>c</sup> Cushion is submergence minus draft; values in brackets are minimums.  
<sup>d</sup> NV = no value available; submergence ranges from 7.5 to 9 ft for Kassinnee River Locks.

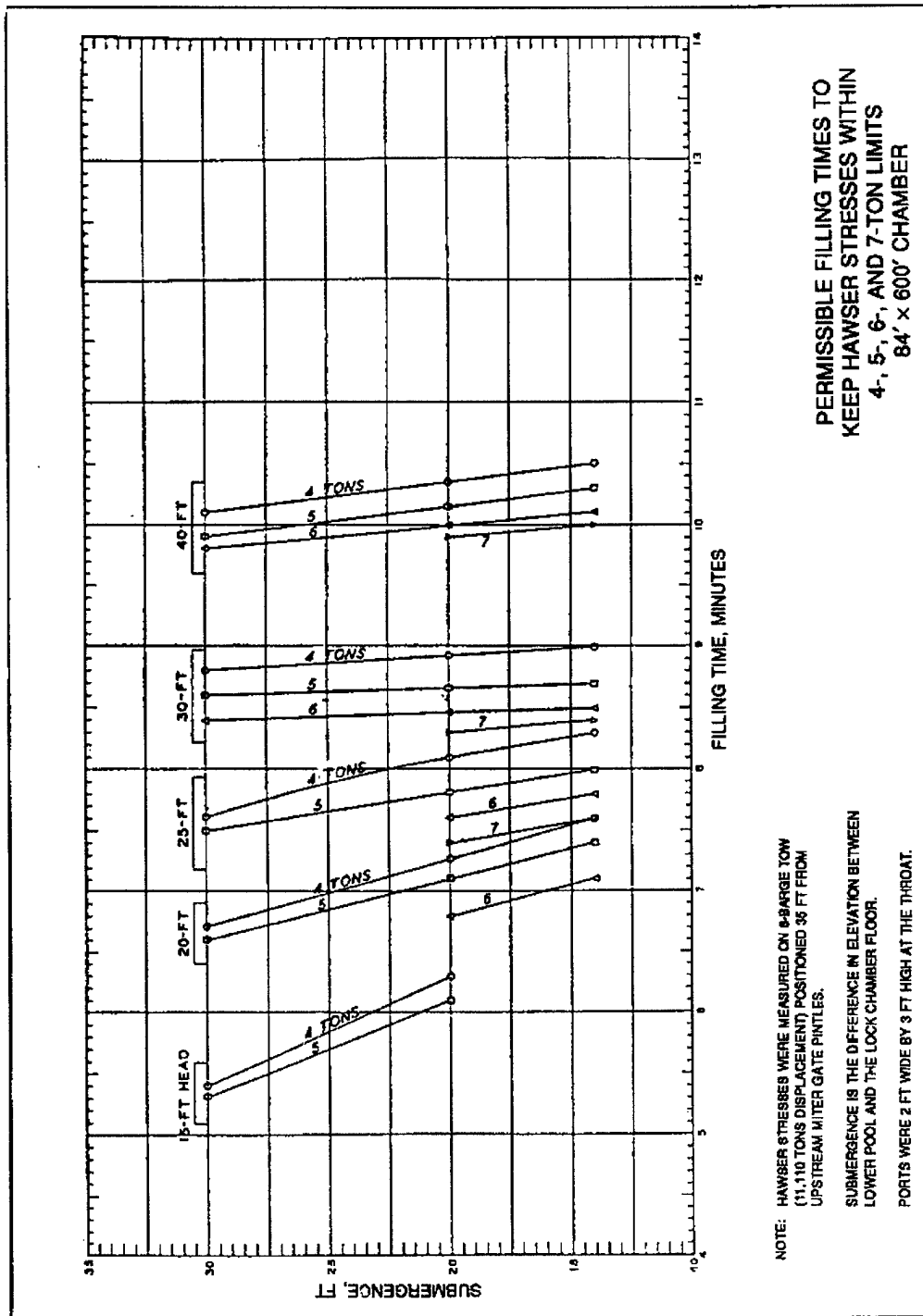


Figure 4-3. Filling time test data. Side-port data are from model tests; the prototype will operate about 10 percent faster

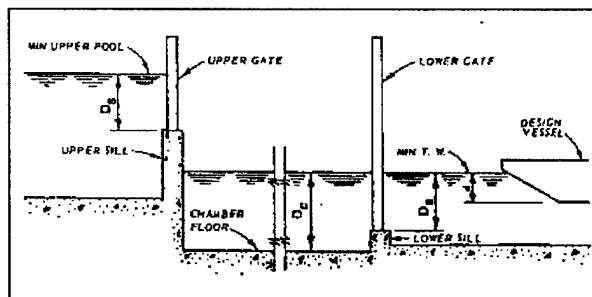


Figure 4-4. Sill elevations

due to safety reasons (item K3). A normal entrance speed of approximately 3 mph requires a sill depth of 2d to avoid excessive squat and loss of vessel speed control. When gate operating clearance above the floor to allow for some accumulation of trash is necessary, either a 2- or 3-ft height of sill above the floor or a floor recess is provided. Since there is very little difference in the cost of the sill versus the cost of the gate, the sill elevation should be kept as low as possible for ease of tow entry and exit and for safety reasons due to the possibility of grounding caused by squat and/or ice accumulation. The upper sill depth should be equal to or greater than the lower sill depth. Consideration can be given to a much greater depth if a need to pass emergency traffic during a loss of pool situation or other exigency is projected. Table 4-3 provides examples of sill depths at some existing projects. The CEWRC-NDC Waterling Bulletin Board System (Navigation and Dredging Data and Reports, Lock Characteristics Data, Physical Characteristics Report) provides a complete listing of Corps locks. The influence of the sill depths due to tailwater and upper pool elevation durations at various levels is part of the economic analysis called for in paragraph 4-6.

**Table 4-3**  
Existing Sill Elevations

Lock	Type	Upper Design ft	D <sub>c</sub> ft	Lower D <sub>s</sub> D <sub>u</sub> ft
Vermilion	SG	15	S	S
Lock 52	SPF	12	15.4	11
Willow Is. Main	SP	25'	35, 18 <sup>b</sup>	15
Ozark	SP	27'	18 <sup>n</sup> , 16 <sup>m</sup>	17 <sup>n</sup> , 14 <sup>m</sup>
Belleville Main	BL2	28'	37, 20 <sup>b</sup>	15
Willow Is. Aux	BL1	25'	35, 18 <sup>b</sup>	15
Bay Springs	HB4	15	21 <sup>n</sup> , 15 <sup>m</sup>	15
Lower Granite	HB8	17	21 <sup>n</sup>	15 <sup>m</sup>

Note: S = same as chamber floor; r = rock floor; b = initial; n = normal; m = minimum; values are for normal pools unless otherwise noted.

#### 4-9. Location of Outlet Structures

Constraints are so that lockage flows (emptying) are a minimum liability to navigation and satisfy other site-specific concerns and so that satisfactory chamber performance is retained. For sector gates the outflow point is the lower gates, and discharge is directly into the lower approach channel. For culvert systems the outflow is either into the approach channel (by means of bottom or side manifolds) or, when possible, into the main river remote from the approach, or by a division of flow between main river and approach canal. Three specific preliminary information needs are as follows.

*a. Navigation.* Discharge hydrographs are required for studies (EM 1110-2-1611) of navigability in the lower approach. Control during emptying is at the outlet ports which, in design, can be modified to increase peak flows (decrease operation time). For preliminary calculation the outflow hydrograph is made identical to the inflow hydrograph (Figure 4-2) although a 10 to 20 percent decrease for peak flow during emptying is not uncommon.

*b. Channel stability.* Discharge hydrographs are required; the estimates (a above) are used for preliminary studies of bed and bank stability. Structures for energy dissipation and stone for bed and bank protection are often required.

*c. Stages.* For remote outlets, the differential between stage at the outlet location and stage in the lower approach channel affects lower gate operation. Values are required for the navigable range of hydrologic conditions at the project.

#### 4-10. Typical Outlet Locations

The outlet structure types in Table 4-4 are from Plates 3-1 to 3-8.

**Table 4-4**  
Outlet Structure Types

Project (Typical)	Outlet Structure Type
Vermilion	Sector gate
Lock 52	Channel side; one multiported structure
Willow Is. Main	Remote; one with two ports
Ozark	Remote; one with two ports
Belleville Main	Remote; two with one port
Willow Is. Aux.	Remote; one structure with one port
Bay Springs	Channel bed; two multiported structures
Lower Granite	Remote; one structure with two ports

## Section II

## Very-Low-Lift Designs

## 4-11. General

Relatively small static and dynamic hydraulic loadings occur for locks with very low lifts (water-surface differential  $H < 10$  ft). In addition, constraints with regard to chamber performance (filling time and hawser stress) are normally sufficiently flexible so that adjustments to the field operating procedure, rather than design information, are used to optimize chamber performance. These adjustments are:

*a. Sector gate (SG) locks.* To obtain satisfactory chamber performance, the gate opening rate, pattern, and duration are finalized in the prototype.

*b. Side-port-and-flume (SPF) locks.* The number and sizing of open ports are chosen during prototype operation.

Model and prototype hydraulic measurements are unavailable for the SPF locks; these design layouts are patterned after low-lift SP systems. Model data (items 19, 20, and 36) are available for SG locks. More rigid constraints or unusual geometric concerns (see item 13, for example) commonly require physical hydraulic model testing (items B9, B11, S7). Overstressing of SG operating machinery during reverse heads (laboratory studies, item 65; prototype studies, item 66) resulted in gate framing and lip designs presented in EM 1110-2-2703 that have not been rated for lock filling and emptying.

## 4-12. Sector Gate Design Concept

The gate and recess, shown in Plate 3-1 with EM 1110-2-2703, are geometrically formed so that the minimum dimension between recess lip and recess boundary equals the clear opening at the lock center line. Flow is distributed across the width of the chamber since the recesses, in addition to the center-line opening, are flow passages.

## 4-13. Hydraulic Evaluation

Sector gate lock studies include four fundamental evaluations:

*a. Operation time.* Longer filling and emptying times are expected for projects requiring larger chamber water-surface areas or having higher lifts. The size and shape of the flow passages through the gate recesses

affect the rate of flow into and out of the chamber as well as affecting the mooring conditions immediately downstream from the gate. The primary means of altering the operation time for a specific sector gate design is by optimizing the rate and extent of gate opening. The values in Table 4-5 apply to constant rate gate opening tests for the Sacramento Barge Canal Lock; see item 36 for a wider range of test conditions.

*b. Chamber mooring conditions.* Velocities and turbulence near the upper gate during filling and lower gate during emptying are unfavorable as mooring conditions. For example, a usable chamber length of about 540 ft, rather than 640 ft, based on gate location is suggested (item 36) for the Sacramento Barge Canal Lock. An alternate solution is slow gate operation.

*c. Hydraulic loadings.* The forces required to open and close the sector gate under normal and reverse flows are sensitive to gate lip shape. Loadings are presented in EM 1110-2-2703 (from items 36 and 65). The more recent results (item 65) are for sector gates operating under reverse heads and provide guidance on gate lip detail.

*d. Flow rate.* The chamber water-surface elevation is evaluated by simultaneously numerically integrating flow rate  $Q$  and elevation  $z$  relationships:

$$Q = cb_g h^{3/2} \quad (4-1)$$

$$Q = A_L \frac{dz}{dt} \quad (4-2)$$

where

$c$  = a coefficient that is assumed constant for free-flow conditions, but under submerged conditions gradually decreases with increased submergence (see Figure 4-5)

$b_g$  = effective gate opening which includes the center-line opening and the gaps through the recesses

$h$  = upper pool water-surface height above the upper sill

$z$  = chamber water-surface height above the upper sill

Table 4-5

Constant Rate Gate Opening Tests (Sacramento Barge Canal, Item 36)

Stage <sup>a</sup> ft	Lift ft	Gate Opening Rate deg/min	Filling Time T min	Emptying Time T min	Maximum Gate Opening	
					Filling deg	Emptying deg
34.5	21	0.33	13.7	20.1	4.6	6.7
		0.66	9.4	13.7	6.2	9.0
29.5	12	0.33	12.5	15.1	4.1	5.0
		0.66	8.8	10.7	5.8	7.1
		1.00	7.2	8.8	7.2	8.8
22.5	6	0.33	12.6	14.3	4.2	4.7
		0.66	8.1	10.1	5.4	6.7
		1.00	7.2	7.8	7.2	7.8

Note:

<sup>a</sup> Stage is referenced to upper gate sill. $A_L$  = lock chamber water-surface area $dz/dt$  = rate of change of the chamber water-surface elevation

Filling is initiated with the upper gates closed and the lock chamber at lower pool level. An example of a calculation for Algiers Lock, item 20, is shown in Figure 4-5. For filling with continuously submerged flow ( $z/h > 0.7$ ), Equation 4-2 in conjunction with the orifice equation is probably more reliable than the above procedure. The flow rate is expressed as

$$Q = cb_g h \sqrt{2g(h - z)} \quad (4-3)$$

in which the coefficient  $c$  is about 0.55 (item S7). Concepts associated with wave action in the chamber and inaccuracies associated with flow calculations for sector gate locks are discussed elsewhere (items S7 and R1, for example). Model and prototype experience, with provision for field adjustment of the sector gate opening pattern, is an essential part of the hydraulic design of sector gate locks.

#### 4-14. Side-port Flume (SPF) Designs

Prototype study data are available from the U.S. Army Engineer District, Louisville. These data include valve operation schedules and operation times for lifts experienced at Locks 52 and 53 (temporary locks). Qualitative information regarding port sizing, flume and chamber performance, and operational experience are

also available. These locks have not been model-tested, so generalized design data are not available.

### Section III

#### Culvert-to-Chamber Systems

#### 4-15. General

The arrangement and sizing of the chamber ports affect chamber performance (hawser stresses, for example) as well as operation time. The flow through the culvert-to-chamber system is bidirectional; that is, the ports are discharge orifices during filling and intakes during emptying. These requirements have resulted in a small set of effective designs (SP, BL1, BL2, HB4, and HB8) that are suited to a reasonably broad range of design constraints. Guidance for the hydraulic design of side-port locks, which have been tested for a very broad range of constraints, is presented in Appendix D.

#### 4-16. Chamber Port Arrangements

The layout of lateral (BL1 and BL2) design is based on model tests conducted for Greenup and Markland Locks (item 43). Small variations in locating and sizing the lateral manifolds have been adopted for design and have performed acceptably in the field. The location of the SP manifolds relative to chamber length follows specific guidelines outlined in Appendix D. The location of the longitudinal manifolds (HB4 and HB8) is invariant; i.e., all chamber details are required to be identical to Bay Springs Lock, HB4, or Lower Granite Lock, HB8. These detail dimensions are available in two model test reports (item 78 for HB4 and item 79 for HB8) and in project

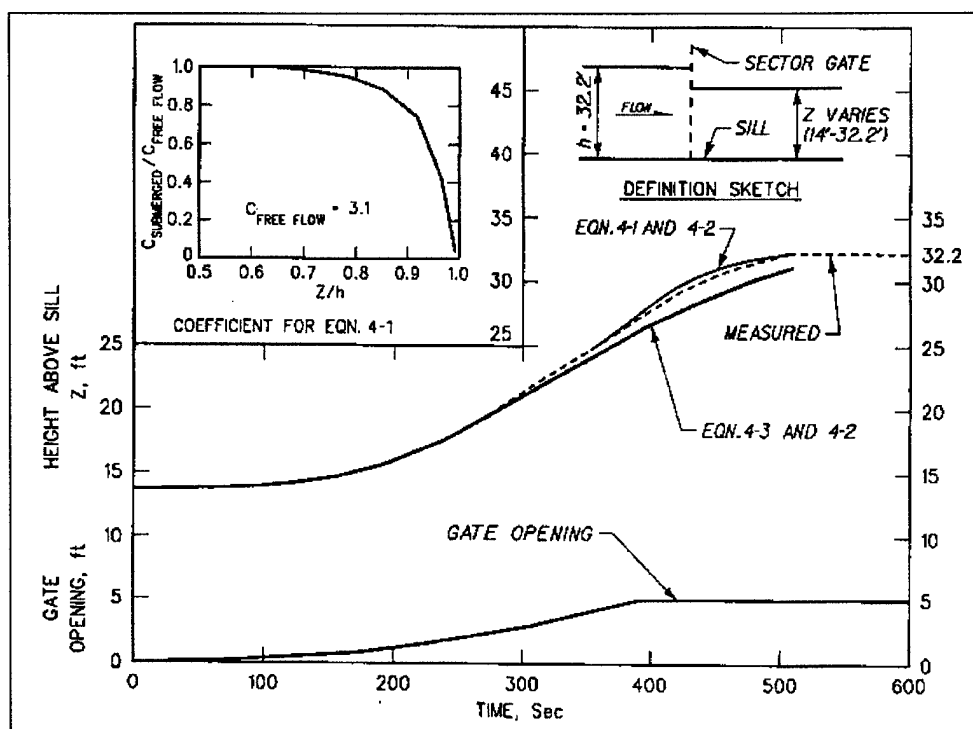


Figure 4-5. Example of Sector Gate Filling (Algiers Lock, Item 20)

construction drawings. Deviations from these details require site-specific hydraulic model studies.

#### 4-17. Flow Passage Areas

The discharge orifice areas (chamber ports for filling and outlet ports for emptying) are primary elements for meeting operation time criteria. The most rapid systems are ones in which these areas are maximized while energy losses within the culverts and manifolds (and valving times) are minimized. Flow passage areas for five lock designs are listed in Table 4-6.

*a. Filling.* Systems that contract from main culvert to chamber (HB8 at Lower Granite) adapt to requirements for rapid filling by using relatively large culverts with minimum losses attributable to culvert features. Energy dissipation is primarily by baffling within the chamber. Systems that expand from main culvert to chamber (BL1, BL2, HB4) adapt to requirements for rapid filling by using relatively large ports with significant energy dissipation occurring within the culverts as well as within the manifold sections. For example, in the Barkley Lock prototype BL2 design (16 ports per lateral, 8 laterals per culvert) the loss is about three times greater

than for a streamlined system (item 71). Similarly, for the Greenup system (18 ports per lateral, 11 laterals per culvert) the loss is nearly six times greater (item 59).

*b. Emptying.* Chamber ports are inefficient as intakes. Efficient systems that contract from chamber to outlet (VB8 at Lower Granite) are designed for longer emptying than filling times and for energy dissipation concentrated downstream from the outlet. Expanding systems (SP at Ozark and VB4 at Bay Springs) tend toward more rapid emptying, although relatively greater losses are caused by chamber ports and manifolds. Deep submergence for water-surface elevations near upper pool reduces the possibility of cavitation within the chamber ports and manifolds during emptying.

#### 4-18. Chamber Ports, Baffles, and Manifolds

Ports for SP systems are discussed in Appendix D. Port and manifold geometries, as used in BL1 and BL2 systems, are shown in Plate 4-1. For lateral systems, ports within a manifold are equally spaced on each wall and equally sized (2.08 ft high by 1.83 ft wide is common); the number of ports per manifold and the number of

Table 4-6  
Flow Passage Areas

Location	Description (Size = Width x Height, ft x ft)						
	Item	Ozark	Willow Island	Belleville	Willow Island	Bay Springs	Lower Granite
Chamber Ports	Type	SP	BL2	BL2	BL1	VB4	VB8
	Number, <sup>a</sup> N <sub>1</sub> Size (Face) <sup>b</sup> Size (Throat)	14 3.25 x 3.50 2.54 x 3.50	24 3.69 x 4.70 2.75 x 4.07	18 1.83 x 2.08 NA <sup>c</sup>	18 1.83 x 2.08 NA	24 1.5 x 3.5 NA	12 1.25 x 3.46 NA
Chamber Manifolds	Number, <sup>d</sup> N <sub>2</sub>	1	1	9	8	2	4
Culvert	Shape	Box	Box	Stepped	Stepped	Box	Box
	Size (Maximum) Size	12 x 12 12 x 12	16 x 18 16 x 18	8 x 5 15 x 16	8 x 5 14 x 16	14 x 9 14 x 14	14 x 9 12 x 22
Outlet Ports	Number, <sup>d</sup> N <sub>3</sub> Shape Size	1 Basin 17 x 12	1 Basin 20 x 16	1 Basin 19 x 16	1 Basin 20 x 16	16 Stepped 3 x 6	1 Basin 12 x 14
Operation	Evaluation	Area Ratios					
Filling	2 + 1	0.78	0.65	NA	NA	NA	NA
	3 + N <sub>1</sub> x 1; 3 + N <sub>1</sub> x 2	0.90; 1.16	0.69; 1.07	0.58	0.58	1.00	1.16
Filling	4 + N <sub>2</sub> x 3	1.00	1.00	0.67	0.70	0.78	1.10
	4 + N <sub>1</sub> x N <sub>2</sub> x 1	0.90	0.69	0.39	0.41	0.78	1.27
Emptying	N <sub>1</sub> x N <sub>2</sub> x 1 + N <sub>3</sub> x 5	0.78	1.30	2.04	1.72	0.88	1.24
	4 + N <sub>3</sub> x 5	0.71	0.90	0.79	0.70	0.68	1.57

Notes:

<sup>a</sup> Per manifold.

<sup>b</sup> Excludes 0.5- to 1.5-ft radius surface contour.

<sup>c</sup> Not applicable.

<sup>d</sup> Per culvert.



manifolds vary between designs. The manifold roof is horizontal, whereas the interior sidewalls are stepped as shown. Port extensions are used when flow alignment, particularly from the upstream ports, during filling is of concern. Baffling is provided at adjacent manifold walls by offsetting ports between manifolds. Ports are chamfered with regard to outflow (filling) and inflow (emptying). Ports for high-lift designs (HB4 and HB8) experience high velocities and are chamfered for flow in either direction as shown in Plate 4-1. Tee baffle walls and baffles located on lock and culvert walls are required. The ratios of total port area to manifold areas are 1.000 and 0.865 for HB4 and HB8, respectively. These values near unity, similar to SP systems, are required for efficiency for bidirectional operation. Values substantially greater, 1.7 for the Greenup system shown in Plate 4-1, are efficient with regard to emptying (i.e., as an intake) but relatively inefficient for filling.

#### Section IV Outlet Systems

### 4-19. General

Discharge outlet systems are the orifice controls for the emptying operation. The dominant chamber performance constraint is operation time as affected by outlet sizing. The dominant downstream approach channel constraint is navigation facility as affected by discharge hydrographs and outlet location (paragraph 4-9). The following distinctions regard sizing:

*a. Expanding systems.* The outlet port area is made greater than the chamber port area normally for the purpose of decreasing operation time. Concurrently, greater energy losses occur within the system (i.e., the chamber ports are not efficient as intakes) so that outflow velocities are also decreased. Both effects are favorable for low-lift locks. For high-lift locks, low local pressures and high pressure fluctuations are associated with expanding high-velocity systems.

*b. Contracting systems.* The outlet port area is made equal to or less than the chamber port area. The common purposes are to raise the hydraulic grade line within the system and to reduce discharge rates within the approach channel at the expense of increased operation time. Contracting systems are best suited for high-lift designs and are rarely appropriate for low lifts.

### 4-20. Design Types

Outlet design variations occur because of options regarding location. General types are outlined in Plate 4-2 as follows:

*a. Manifolds in approach channel floor.* One or several manifolds from each emptying culvert extend across the approach channel. The Bay Springs design results in uniform transverse flow distribution near the lock. The new Bonneville design requires the channel expansion (as tested for the Dalles lock, item 52) to be initiated near the manifolds in order to attain a uniform flow within the approach channel. The new Bonneville system contracts (discharge port area to chamber port area ratio equals 0.83) whereas the Bay Springs system expands (ratio equals 1.14, item 78). The St. Anthony Falls Lower Lock is an example of large expansion and uses four lateral manifolds branching from one discharge culvert (item 44).

*b. Manifolds in guide and guard wall.* Two such expanding systems are shown in Plate 4-2. The Trinity River model test manifold discharges directly into the lock approach (item 74). The New Cumberland Main Lock discharge is subdivided by the main lock into river, main approach, and auxiliary approach components (item 21). The Trinity River system requires baffles at each port. These types of approach-channel manifolds are low cost and are well-suited for low-lift projects when higher velocities and turbulence in the approach near the lock are acceptable (as contrasted with remote outlets, *c* and *d* below).

*c. Basins.* Normally and when economically feasible, the most favorable outlet location as regards navigation is in the main river remote from the lock approach. Basins used for these outlets are as shown in Plate 4-2. The Greenup Lock type basin is relatively deeply submerged (item 43) so that energy dissipation within the flow exterior to the basin is acceptable. The Jackson Lock type is designed (item 32) as a stilling basin; test data pertain to designs without and with various spacings of baffle blocks and end sill. Lower Granite (high-lift) uses a Greenup-type basin with a contraction (discharge port area to chamber port area ratio equals 0.80). Ozark Lock (low-lift) uses a Jackson Lock unbaffled basin with an expansion (ratio equals 1.29).

*d. Other types.* The outlet may be placed (usually remotely) so that other outlet structures as used elsewhere (outlet works for example) suit a site-specific design. The structure must:

(1) Provide conditions (particularly with regard to navigation) in the lower approach that are satisfactory.

(2) Have expansion or contraction conditions between chamber manifolds and outlet that are acceptable with regard to chamber performance.

(3) Provide a capability for reliably handling structural and hydraulic needs (particularly large intermittent discharges) during lock chamber emptying.

#### Section V Intakes

### 4-21. General

Intake flows are essentially unidirectional. The design pertains to filling only and seeks to accomplish the following objectives.

*a. Navigation and sedimentation.* The location and orientation are such that adverse effects on navigation and channel sedimentation are avoided (see constraints, Chapter 2).

*b. Debris and ice.* The elimination of debris from the culvert normally requires trashracks at the intakes. These are placed on the wall face (common) or immediately within the wall structure (Lower Granite, item 79). The reduction of clogging at the intakes and sediment transport into the culverts is of obvious benefit in terms of lock maintenance (see paragraph 3-13). Trashracks must be secured for small reverse loadings that occur during lock chamber overfill.

*c. Velocities.* The intake is designed as a highly convergent streamlined manifold having the concurrent objectives of equal flow distribution through the ports and small energy loss. Small energy loss contributes to efficient lock filling and, for two-culvert systems, enables equal culvert flows to be attained with substantially different intake configurations. Low velocities through the trashbars place less stress (and reduce the possibility of flow-induced vibration) on the exposed structural elements. Existing rack structures are generally conservative for peak velocities less than 4 feet per second

(fps); higher velocities may require special attention (EM 1110-2-1602; EM 1110-2-2602).

*d. Vorticity.* The formation of large vortices at lock intakes is considered highly undesirable because of hazard to small vessels, imbalance between culvert flows, and damage to trashrack. The elimination of vortex action for a specific filling pattern requires studies (see Chapter 5, Section VIII) of the following items:

(1) *Local geometry and flow constraints.* Geologic and structural features, such as the shape and orientation of guide and guard walls, may introduce vorticity into the intake flow. Similarly, adjacent spillway or river flows may result in vortex formation under a particular format of overall project operation. An intake located outside the approach channel so that navigation is not affected by vorticity over the intake structure is advantageous at many projects.

(2) *Structure type.* Generally, for small submergence, intakes are long and shallow with numerous ports (8-12 are not uncommon); a uniform distribution of flows over the length of the structure tends to reduce vortex formation. Short and high intakes (four ports at Lower Granite) may function satisfactorily when deeply submerged.

(3) *Submergence.* Deeply submerged intakes (see EM 1110-2-1602) are generally less prone to vorticity than these with shallow submergence. Extrapolating submergence effects based solely on changing upper pool levels as compared to changing intake elevation (with fixed pool level) is questionable because of local geometry.

(4) *Operation.* Vorticity intensifies as the valve is opened and persists during and sometimes beyond the lock-filling period. Operational situations, particularly valve opening times and maximum flow values, are important.

### 4-22. Design Types

Examples of intake structures are shown in Plate 4-3 with layout parameters listed in Table 4-7. These and other intakes have been studied (physical hydraulic models) and adopted for site-specific application.

**Table 4-7**  
**Examples of Model-Tested Intake Layouts<sup>a</sup>**

Lock	Lift ft	Q cfs	No. of Ports	Port		Manifold Length ft	Pier Thickness ft	Submer- gence ft
				Height ft	Width ft			
Holt	63.6	7,000	1	31	18	18	NA	46.5
Lower Granite	105.0	13,600	4	30	8	47	5	58.0
Greenup	32	7,000	8	12 <sup>b</sup>	8	99	5	14.0
Bay Springs	84	9,100	10	14	7	115	5	48.0
Dardanella	54	6,000	13	13	7	151	5	24.0
Barkley	57	4,400	2 × 4	13	7.5	66	12	29.0
Dardanella	54	6,000	2 × 7	13	7	79	5	24.0

Note:

<sup>a</sup> Dimensions exclude rounding at the wall face.<sup>b</sup> 4-ft-high sill, culvert at intake 18 ft wide by 16 ft high.

## Section VI

### Filling-and-Emptying Valve Systems

#### 4-23. General

Recent lock designs use reverse tainter valves for flow control. Alternate valve types provide less desirable hydraulic, structural, operational, or economic conditions. The normal tainter valve (skinplate upstream) has been replaced for lock design by the reverse tainter valve (skinplate downstream) because of the ease of regulating air demand for the latter design. The normal valve is not precluded from lock design (particularly as an emptying valve); however, current practice is to use the reverse tainter valve for emptying as well as filling. Comprehensive design guidance presented in EM 1110-2-1610 provides details regarding valve types, loadings, losses, etc.; this discussion is limited to an overview of the valves as they relate to the overall filling-and-emptying arrangement. The following paragraphs deal exclusively with reverse tainter valves.

#### 4-24. Valve Sizing

By using streamlined contractions upstream and gradual expansions downstream, the valves can be sized substantially smaller than the main culvert section. Section area changes commonly are accomplished by a change in culvert roof elevation rather than offsetting the culvert walls. Large valves (e.g., 18 ft high by 16 ft wide) are designed

for the new Gallipolis low-lift lock. The extreme contraction-and-expansion design is at the Lower Granite high-lift lock, which, for a 22-ft-high by 12-ft-wide main culvert, uses 14-ft-high by 12-ft-wide filling-and-emptying valves. The advantage of small valves is lower cost particularly, because of the greater loading, at high-lift projects. Higher velocities and lower pressures at the valve location occur for small valve designs during valve full open conditions.

#### 4-25. Valve Siting

Structural, operational, and economic considerations for valve siting must satisfy the following hydraulics topics.

*a. Position along the culvert.* The filling valve, downstream from the intake manifold, and the emptying valve, upstream from the outlet, are separated from the culvert-to-chamber system by a streamlined transition conduit. The fundamental requirement is that the distribution of flow into and out of the culvert-to-chamber system is not unbalanced due to nonuniformity in the adjacent main conduit flow. Current guidance requires a distance of 6.5 culvert heights (as measured at the filling valve) between the filling valve and the culvert-to-chamber system (EM 1110-2-1610).

*b. Elevation.* The hydraulic consideration is pressure downstream from the valves that contributes to air entrainment and cavitation. Entrained air, particularly for

**30 Jun 95**

low-lift locks, may accumulate in the culverts as a pressurized air mass with the potential for bursting through the water surface and through vents and wells. Well-mixed air is more common for high velocities associated with high-lift locks and, when excessive, causes a frothy condition at the outflow water surface. Guidance on air entrainment is included in EM 1110-2-1610. Cavitation, particularly at high-lift locks, may cause surficial damage to culvert walls, valve seals, and other exposed valve components. A condition in which cavitation causes pressure shock waves to occur in the flow downstream from the valve is resolved during design by either air venting the low-pressure region below the valve so that air rather than vapor pockets occur; setting the valve at a low elevation so that vapor pressures do not occur; or using a less efficient system also so that vapor pressures do not occur. Guidance for avoiding cavitation is included in EM 1110-2-1610.

#### *Section VII*

#### *Culvert Layouts*

### **4-26. General**

The culvert geometry includes bends, contractions, expansions, junctions, bifurcations, etc., as required to resolve the plan and profile layout of the intake, valves, culvert-to-chamber, and outlet systems. Recent designs use rectangular culverts. The aspect ratios (height to width) near 1.0 are common although values as extreme as 1.6 and 0.6 have occasionally been used. Ratios at the valve location (18:16, 14:12, 12:12, etc.) are always near unity for valve structure and economy reasons. Hydraulic design parameters, such as those included in

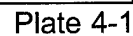
EM 1110-2-1602, are equally applicable to lock culverts provided allowance is made for the normally short spacing between components and the unsteady nature of lock flows. Published compilations (item M9, for example) and studies (item M5, for example) provide useful hydraulics guidance.

### **4-27. Contracting and Expanding Systems**

System sizing (intake, filling valve, culvert-to-chamber, emptying valve, and outlet) establishes the extent of section area and shape changes within the culvert. These changes (examples are illustrated in Plates 3-3 and 3-4, SP systems; Plates 3-5 and 3-6, BL1 and BL2 systems; Plates 3-7 and 3-8, HB4 and HB8 systems) are particularly susceptible to separation at boundaries introducing energy loss, turbulence, and, particularly for high-lift locks, cavitation effects into the flow. To avoid these problems, expansions are normally gradual (roof expansions 1V:6H to 1V:10H are common) and contractions are streamlined. The flare of each SP port sidewall, for example, is about 3 degrees for filling; rounding at port intakes and outlets has ranged from about 0.5 to 2.0 ft.

### **4-28. Other Transitions**

Numerous transitions have been used and tested for lock designs. Hydraulic model and prototype studies (see Appendix C) are sources of information regarding application or previous use in lock design. EM 1110-2-1602, other hydraulics design manuals, and published references (item M9, for example) provide useful guidance for hydraulic design.





## LATERAL MANIFOLDS



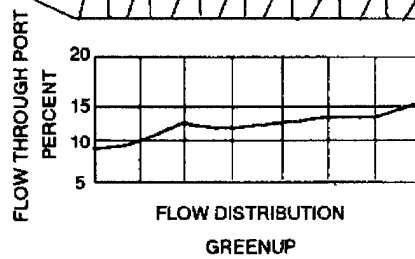
TRINITY RIVER LOCKS  
WALL MANIFOLDS



## BASINS

## OUTLET TYPES

### Plate 4-2



**4-17**

## Chapter 5 Special Hydraulic Study Topics

### Section I Introduction

#### 5-1. Baseline Analysis

The hydraulic analyses of lock filling and lock emptying require an unsteady flow formulation that includes the decreasing head caused by the rise or fall of the chamber water surface. The objective is to determine, as a function of time, three basic quantities:

- a. Chamber water-surface elevation.
- b. Flow rate exiting (filling) or entering (emptying) each of the chamber manifolds.
- c. Hydraulic grade line from the reservoir intakes to the lock chamber (filling) or from the lock chamber to the outlets (emptying). The grade lines include valve wells and other attached flow passages.

#### 5-2. Baseline Constraints

Conditions normally imposed on the analysis are chamber, approach, and system geometries and hydraulic characteristics; initial upper, lower, and chamber water-surface elevations; valve geometry, opening pattern, and hydraulic characteristics; type of valving (commonly two synchronous valves or single valve); and type of operation (filling, emptying, or steady flow). Nonroutine conditions, such as instantaneous valving and bulkhead failures, may also require consideration during hydraulic design. The analysis, excluding mathematical considerations, varies in precision from lock to lock due to the following factors.

a. *Stubby culverts.* Lock culverts are short and contain elements (manifolds, valves, bends, transitions, etc.) in proximity. Published hydraulic coefficients as tested for individual elements are in error when directly applied to the composite system. Best results are obtained when culvert system coefficients are derived from a geometrically similar model or prototype.

b. *Unusual shapes.* The intake, chamber, and outlet manifolds, particularly, are function specific. Published data for nonlock manifolds are useful in concept but rarely in detail for the shapes used for lock design. Other unusual shapes and combinations of elements are

not uncommon. Useful data, when available for these unusual geometries, generally come from previous lock hydraulic model or prototype tests.

c. *Flow acceleration.* Analysis, based on incompressible unsteady flow, is similar to established procedures (surge tank design, for example). However, specific information regarding the significance of wells, branches, junctions, ports, etc., is very limited. These information gaps are resolved, to the extent possible during design, by comparison with solutions for similar locks.

#### 5-3. Analysis Results

The baseline analysis (paragraph 5-1) provides the basic quantities required as input for the design of individual flow passage elements. Conventional hydraulic practice applies to the design details.

### Section II Steady Flow in Lock Culverts

#### 5-4. Discharge

For constant valve opening and fixed pool levels, the flow rate is given by an orifice discharge equation:

$$Q = CA \sqrt{2gH} \quad (5-1)$$

in which

$Q$  = discharge per culvert, cubic feet per second (cfs)

$A$  = reference cross-sectional orifice area, square feet (ft)

$g$  = gravitational acceleration, 32.2 ft/second (sec)<sup>2</sup>

$H$  = difference in pool levels (head), ft. The difference is upper pool to chamber for filling and chamber to lower pool for emptying

$C$  = discharge coefficient (referenced to area  $A$ )

The value of  $C$ , a measure of the efficiency of the design, depends on:

a. *Reference area.* The accepted practice is to use the cross-sectional area  $A_c$  at the culvert immediately downstream of the valve as the reference area  $A$  in Equation 5-1. Consequently, systems having small



valves (relative to total efflux area) in culverts with streamlined contractions and expansions have large  $C$  values; systems with large valves having essentially the same  $Q$  and  $H$  relationship erroneously appear less efficient because of low  $C$  values.

*b. Exit port geometry.* Streamlining the efflux ports tends to increase efficiency (i.e., increasing  $Q$  for unchanged  $H$  corresponding to a larger  $C$  value). Similarly, increasing the total port area  $A_p$  tends to increase efficiency. However, observations indicate that when  $A_p$  exceeds about 1.1 times the manifold section area, no additional increase of  $Q$  is attained.

*c. Energy loss.* Head losses occur throughout the flow passage. Systems with streamlined transitions, smooth and short culverts, few boundary changes, and efficient manifolds have high  $C$  values.

## 5-5. Energy Loss Coefficient

The overall energy loss coefficient  $k_t$  is defined and compared to the discharge coefficient  $C$  (Equation 5-1) as:

$$k_t = \frac{H}{V^2/2g} = \frac{1}{C^2} \quad (5-2)$$

where

$V = Q/A_c$  = mean velocity at the reference section, fps. A range in  $C$  values from 0.5 to 0.9 corresponds to  $k_t$  values from 4 to 1.2; this range includes nearly all existing CE lock designs for either filling or emptying.

## 5-6. Individual Losses

The sum of individual loss contributions, boundary losses plus losses due to numerous form changes, as calculated using published friction and form loss coefficient values exceeds losses observed for lock filling-and-emptying systems. This difference is attributed to having stubby culverts (i.e., inadequate spacing so that established flow is not reached between identifiable boundary changes). Such summations are avoided in analysis by using model and prototype test data reduced to the form shown schematically in Figure 5-1.

## 5-7. Reynolds Number

Higher flow rates occur in prototype lock culverts than are predicted from model observations. This difference

is attributed to a decrease in loss coefficient values corresponding to the much larger Reynolds number  $R$  for prototype flows. Reynold's number is defined as

$$R = VD_h/\nu \quad (5-3)$$

where

$D_h$  = hydraulic diameter;  $D_h = A_c/P_c$  where  $P_c$ , ft, is the culvert perimeter at the reference section

$\nu$  = kinematic viscosity (for example,  $\nu = 1.05 \times 10^{-5}$  ft<sup>2</sup>/sec for water at 70 °F and atmospheric pressure)

For a 1:25-scale model (common size, see Chapter 6) the difference in Reynolds number is 125-fold due to geometry alone. The Darcy-Weisbach friction factor is defined as

$$f = \frac{D_h}{L} \frac{H_L}{V^2/2g} \quad (5-4)$$

where

$H_L$  = energy loss, in ft, over a length  $L$  in ft, of uniform conduit. For smooth boundaries, the reduction in  $f$  from a peak model  $R$  (say  $10^5$ ) to a peak prototype  $R$  (say  $1.25 \times 10^7$ ) is from 0.018 to 0.008.

## 5-8. Energy-Loss Coefficient Values

This illustration uses Lower Granite Lock model test data reduced to the form shown in Figure 5-1 as listed in Tables 5-1, filling, and 5-2, emptying. Data are for two valves fully opened and steady flow.

*a. Inflow (filling).* Typically, the intake is a highly efficient combining-flow manifold, and the point of measurement (Table 5-1) is upstream of the region within which the velocity profile is restructured to culvert flow. Consequently the  $k_i$  value is low, ranging from near 0.05 to about 0.15. Higher values may occur with a small total port area, trashrack blockage, or inefficient approach conditions.

*b. Upstream culvert (filling).* This segment of a filling culvert is commonly convergent; vertical and horizontal bends and other changes in form and alignment vary significantly between projects. The  $k_2$  value,

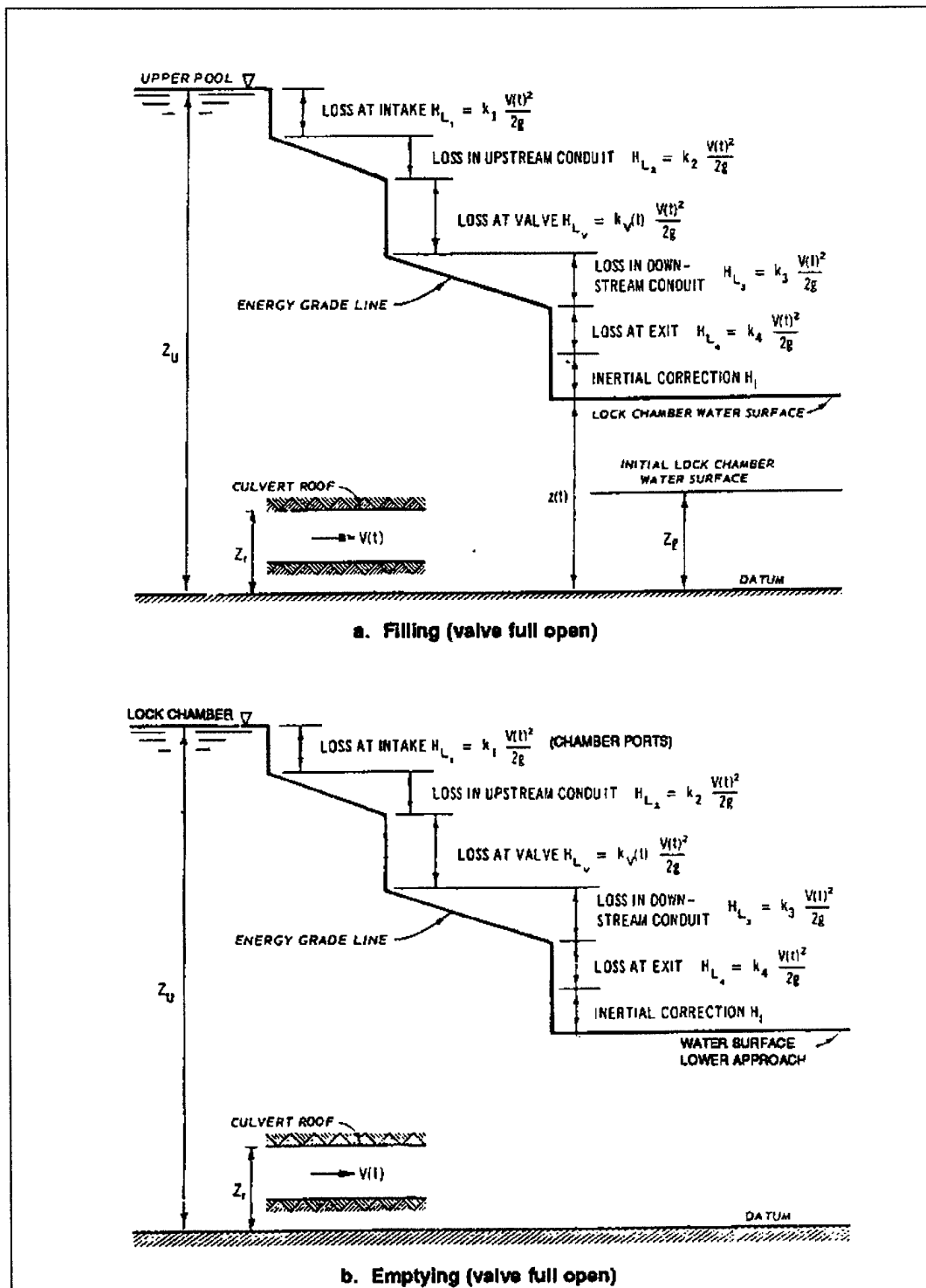


Figure 5-1. Hydraulic grade line determination. The schematics show common measurement locations and coefficients determinable from most model and prototype experimental studies. Steady flow conditions apply. Symbols are defined in Appendix H.

**Table 5-1**  
**Filling Culvert Loss Coefficient Example; Two Valves Full Open With Steady Flow (Lower Granite Lock, Item 79: BHL, TR No. 126-1, Table J)**

Symbol <sup>a</sup>	Location	Coefficient with Reference
		Area = 168 ft. <sup>2</sup>
$k_1$	Intake	0.08
$k_2$	US culvert	0.25
$k_{v,100}$	Valve	0.045
$k_3$	DS culvert	0.07
$k_4$	Chamber	1.19

Notes:

- a. Notation is described in Figure 5-1a.  
b.  $k_t = 0.08 + 0.25 + 0.045 + 0.07 + 1.19 = 1.635$

**Table 5-2**  
**Emptying Culvert Loss Coefficient Example; Two Valves Full Open With Steady Flow (Lower Granite Lock Item 79: BHL, TR No. 126-1, Table M)**

Symbol <sup>a</sup>	Location	Coefficient with Reference
		Area = 168 ft. <sup>2</sup>
$k_1$	Chamber	1.40
$k_2$	US culvert	0.24
$k_{v,100}$	Valve	0.045
$k_3$	DS culvert	0.16
$k_4$	Outlet	0.79

Notes:

- a. Notation is described in Figure 5-1b.  
b.  $k_t = 1.40 + 0.24 + 0.045 + 0.16 + 0.79 = 2.635$

0.25 in Table 5-1, includes losses incurred at the intake as well as boundary and form effects on the flow within the culvert upstream from the filling valve.

c. *Valve (filling)*. Valve loss coefficients, as determined from experimental data for valves in long culverts, are used (see Section IV). For valves located in a non-expanding culvert the  $k_{v,100}$  value is 0.045 as shown in Tables 5-1 and 5-2.

d. *Downstream culvert (filling)*. This segment is commonly of constant section although variations occur (for example, Lower Granite is highly divergent). The determination as to whether the expansion affects valve loss (i.e., nearer to the valve than at Lower Granite) is described in Section IV. A low value,  $k_3$  equals 0.07 in

Table 5-1, is common particularly when effects of the more complex geometrical features are included in the chamber outlet loss.

e. *Efflux (filling)*. The chamber manifold ports are orifice-type controls during filling. The value of  $k_4$  decreases toward a minimum expected value of about 1.2 as the total port-to-manifold section area ratio increases to unity. Further increase in port area tends to cause little or no decrease in exit loss coefficient values. The value  $k_4$  equals 1.19 in Table 5-1 includes effects due to the long and complex crossover geometry combined with a ratio equal to 0.84. More efficient filling (and emptying) would be expected with a ratio nearer to unity.

f. *Overall loss (filling)*. Using reference-area values from Table 5-1, the filling loss,  $k_t = 1.64$ , corresponds to a discharge coefficient value,  $C = \sqrt{1/k_t} = 0.78$ . Typically  $C$  filling values range from about 0.5 for inefficient systems, to 0.90 for highly efficient systems, although choice of reference area (valve sizing) can distort these values in a misleading manner.

g. *Inflow (emptying)*. The chamber manifolds are inefficient intake devices (manifold loss coefficient  $k_m$  equal to 0.84 in Table 5-2), and when a complex culvert arrangement such as that at Lower Granite is included, a high  $k_1$  value for emptying occurs.

h. *Upstream culvert (emptying)*. The emptying culvert is commonly of constant section although variations occur (for example, Lower Granite is highly convergent). The  $k_2$  value, 0.24 in Table 5-2, includes losses incurred upstream as well as boundary and form effects on the flow within the indicated culvert length.

i. *Valve (emptying)*. Refer to c above.

j. *Downstream culvert (emptying)*. This segment is commonly of constant section although variations occur. The losses occurring within this segment at Lower Granite are considered negligible;  $k_3$  equals 0.16 in Table 5-2.

k. *Efflux (emptying)*. The outlets are orifice-type control during emptying; a value of  $k_4$  near unity is expected for an efflux-area-to-reference ratio of one. The low value, 0.79 in Table 5-2, depicts to an unknown extent a larger effective efflux area (due to sidewall flare in the basin).

l. *Overall loss (emptying)*. From Table 5-2, the emptying loss  $k_t$  equals 2.64, corresponding to a

discharge coefficient  $C$  of 0.62. Typically, emptying  $C$  values are similar in range to filling values. Distortions due to choice of reference area also occur and, for the same lock, a lower emptying than filling  $C$  value is not uncommon.

### Section III

#### Lock Filling and Emptying

## 5-9. General Features

*a. Filling.* During a filling run, as sketched in Figure 5-2(a), valve movement is initiated at time  $t$  equals zero. The initial differential head  $H$  is the difference in elevation between the upper and lower pools (i.e.,  $H = Z_U - Z_L$ ). The rate of rise,  $dz/dt$ , of the lock water surface increases to a maximum at time  $t_m$  after which it decreases continuously, reaching zero at time  $t_f$ . The valve is fully open at time  $t_v$ . The operation time (or filling time) is designated as  $T$ . The inertia of the water in the filling system causes the lock water surface to rise the distance  $d_f$  termed the overtravel (or overfill) above upper pool, which occurs at time  $t_f$ .

*b. Emptying.* Parameters describing an emptying run (Figure 5-2(b)) are analogous to those of a filling run. For example, during emptying, the water surface tends to lower the distance  $d_e$  termed overtravel (or overempty) below lower pool, which occurs at time  $t_e$ .

## 5-10. Valve Operation

As noted in Figure 5-2, the valve hoist and linkage mechanism normally result in a nonlinear relationship between relative valve opening ( $b/B$ ) and opening time ( $t/t_v$ ) where  $b$  is the vertical gate opening,  $B$  is culvert height,  $t$  is time, and  $t_v$  is the valve operating time period. The pattern sag varies depending on the valve and linkage geometry and on the operating mechanism. The sag, when  $t/t_v$  is equal to 0.5, varies between 0.4 (large sag) and 0.1 (small sag). The following are variations in valve operation (applicable to either filling or emptying):

*a. Normal two-valve (synchronous).* Flow is through two culverts; the valves' operating mechanisms are identical and mechanically and electrically synchronized so that identical valve patterns are obtained. This is the type of valving preferred for normal lock operation.

*b. Single valve.* Filling or emptying with one valve (in a two-valve system) may be required for emergency or operation and maintenance reasons. Satisfactory chamber performance using one-valve operation is

needed although longer operation times are usually acceptable.

*c. Nonsynchronous valves.* For this two-valve operation, either or both start time and opening rate differ between valves. This is not general design practice. However, prototype mechanisms and operating procedures contain many examples of designs deteriorated from synchronous into some form of nonsynchronous valving.

*d. Stepped valves.* The valves are opened to a particular value (commonly about one-fourth open), maintained in that position for some delay time period, then opened to full open. Stepped valving is not usually a design choice. However, certain postconstruction requirements for raising culvert pressures or reducing chamber oscillations have been resolved by means of stepped valves.

*e. Special valve patterns.* Smoothed (but essentially stepped) patterns are obtained using cams in the valve hoist mechanism for purposes similar to stepped valving.

*f. Overtravel control.* The extent of overtravel ( $d_f$  or  $d_e$  in Figure 5-2) is reduced by initiating valve closure prior to the normal lock operating time. Valve closure for many existing locks is initiated automatically using a differential water-surface-level sensor.

*g. Valve opening time.* Rapid valve times (near 1 min) are an existing design goal. The slow valving (8 min or greater) that is used at certain locks should be unnecessary for new lock designs.

## 5-11. Lock Coefficient

The continuity relationship between culvert flow and chamber rate-of-rise when combined with steady-flow discharge coefficient (Equation 5-1) is the basis for the traditional empirical lock design equation (item P4). The solution is modified to include effects due to flow acceleration and valve opening pattern

$$T - Kt_v = \frac{2 A_L [(H + d_f)^{1/2} - d_f^{1/2}]}{n A_c C_L \sqrt{2g}} \quad (5-5)$$

where

$T$  = lock filling time, sec

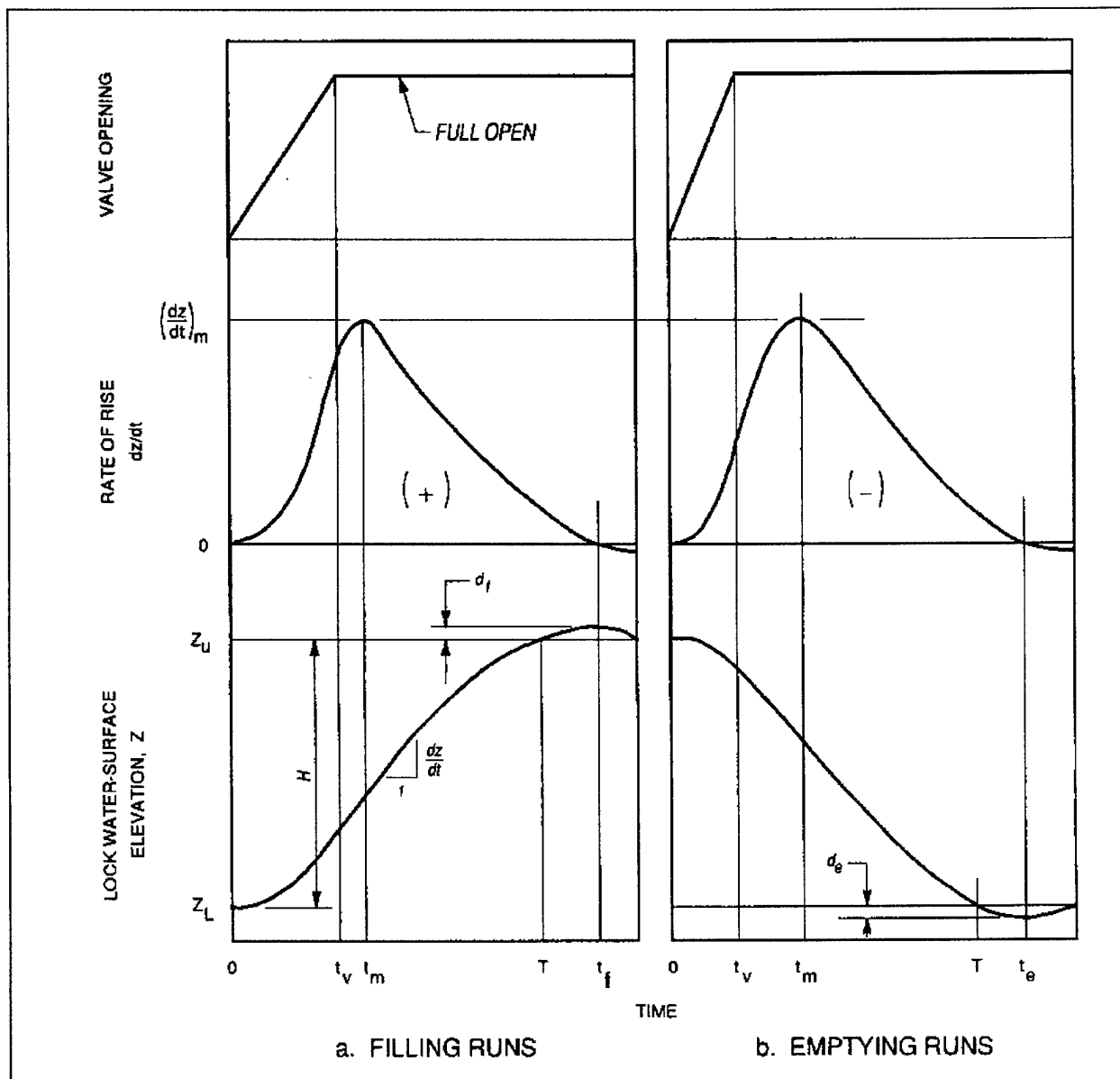


Figure 5-2. Lock filling and emptying (definition sketch)

$K$  = overall valve coefficient (not a loss coefficient)

$t_v$  = valve opening time, sec

$A_L$  = chamber surface area,  $\text{ft}^2$

$H$  = initial head (i.e., lift), ft

$d_f$  = overtravel, ft

$n$  = number of valves used, 1 or 2

$A$  = culvert area at the valves,  $\text{ft}^2$

$C_L$  = overall lock coefficient

$g$  = acceleration of gravity, 32.2 ft/sec<sup>2</sup>

Equation 5-5 is adequate for preliminary study purposes only. A full hydraulic analysis requires numerical completed simulation of the system.

## 5-12. Operation Time Estimates

Equation 5-5 provides an acceptable estimate of lock operation time subject to the following observations.

a. The valve coefficient  $K$  is normally set equal to 0.5, but a variation from 0.4 to 0.6 occurs in practice. Equation 5-5 is therefore more reliable for rapid (instantaneous for model tests) valving.

b. The lock coefficient  $C_L$  for existing locks ranges from about 0.45 (relatively slow operation) to about 0.90 (rapid operation). However, since reference area  $A_c$  varies due to culvert roof expansions between otherwise similar locks, comparisons based solely on  $C_L$  may be misleading. The discharge coefficient  $C$  differs from  $C_L$  due to factors (Reynolds number, flow acceleration, valve pattern, etc.) not adequately incorporated into Equation 5-5.

c. The overtravel  $d_f$  is normally unknown (ranging from near 1 ft for short inefficient culverts to greater than 4 ft for long efficient systems). The relative insensitivity of filling time to overtravel value causes rough estimates to be within acceptable accuracy.

## 5-13. Basis For Numerical Simulations

The extent of hydraulic detail required in design calculations varies. Higher velocity systems (high lifts) require more detailed grade line elevation and velocity histograms so that energy losses, local velocities and pressures, air entrainment characteristics, surface and form cavitation potential, etc., can be evaluated. These evaluations should use references such as Hydraulic Design Criteria (HDC), EM 1110-2-1602, and other closed conduit flow guidance documents to supplement the hydraulic calculations described in *a - e* below.

a. The following summary of equations is an intermediate approach relating to lock filling which applies to emptying provided appropriate sign changes are included. "The overall head loss in the system is assumed to be made up of the five components listed below. Figure 5-3 shows an example of how the pressure gradient and the lock water surface (an indicator of overall head losses) vary with filling time."

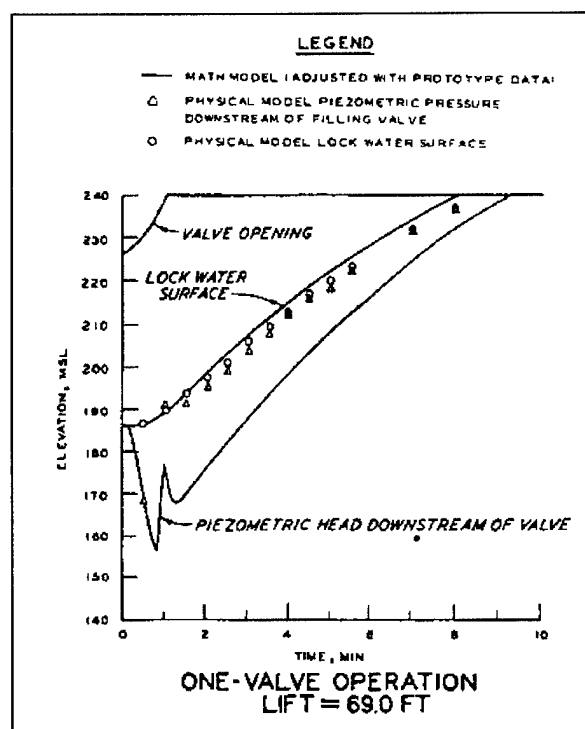


Figure 5-3. Schematic of the lock chamber (filling)

- (1) Intake

$$H_{L1} = k_1 \frac{V^2}{2g} \quad (5-6)$$

- (2) Upstream conduit

$$H_{L2} = \frac{k_2 V^2}{2g} \quad (5-7)$$

- (3) Valve and valve well

$$H_{L3} = \frac{k_v V^2}{2g} \quad (5-8)$$

- (4) Downstream conduit

$$H_{L4} = \frac{k_4 V^2}{2g} \quad (5-9)$$

- (5) Outlet

30 Jun 95

$$H_{L4} = \frac{k_4 V^2}{2g} \quad (5-10)$$

The overall loss  $H_{L4}$  is

$$H_{L4} = (k_1 + k_2 + k_v + k_3 + k_4) \frac{V^2}{2g} \quad (5-11)$$

or

$$H_{L4} = \frac{k_t V^2}{2g} \quad (5-12)$$

Coefficients  $k_1$ ,  $k_v$ , and  $k_4$  are taken to be essentially form-dependent; coefficients  $k_2$  and  $k_3$  are not only affected by form but also by Reynolds number and relative roughness. However, in view of the "stubby" conduits and the dominance of form effects in a lock system, the conduit coefficients  $k_2$  and  $k_3$  can reasonably be assumed constant for either model or prototype, bearing in mind that significant differences may exist between the model and the prototype values.

b. Since the flow is incompressible, the inertial effect is treated as a lumped quantity, that is

$$H_m = \frac{L_m dV}{g dt} \quad (5-13)$$

where

$H_m$  = overall inertial effect

$L_m$  = inertial length coefficient

$$L_m = A_c \sum_{i=1}^m \frac{L_i \alpha_i}{A_i} \quad (5-14)$$

for a conduit made up of  $m$  sections of lengths  $L_i$ , areas  $A_i$ , and flow ratios  $\alpha_i$  (i.e.,  $\alpha_i = Q_i/Q$  where  $Q_i$  is the flow through the  $i^{\text{th}}$  section).

c. The water-surface differential,  $Z_U - z$  in Figure 5-2, is the sum of the inertial effect (Equation 5-13) and the energy losses (Equation 5-5) or

$$\frac{k_t V^2}{2g} = (Z_U - z) - \frac{L_m dV}{g dt} \quad (5-15)$$

d. Continuity applies to the culvert flow ( $nA_c V$ ) and the rate-of-rise,  $A_L dz/dt$ , of the lock chamber water surface

$$V = \frac{A_L dz}{nA_c dt} \quad (5-16)$$

and

$$\frac{dV}{dt} = \frac{A_L}{nA_c} \frac{d^2 z}{dt^2} \quad (5-17)$$

e. Integration of Equation 5-15 (with  $k_t$  = constant and for reasonably high lifts)

$$\frac{dV}{dt} = \frac{-gnA_c}{k_t A_L} \quad (5-18)$$

$$k_t = \frac{-g \frac{nA_c^2}{A_L}}{\frac{d^2 z}{dt^2}} \quad (5-19)$$

f. Similarly, for overtravel,

$$d_f = \frac{L_m nA_c}{k_t A_L} \quad (5-20)$$

or

$$L_m = \frac{d_f k_t A_L}{nA_c} \quad (5-21)$$

Since the possible measurement error for  $d_f$  is always large, Equation 5-21 is not an appropriate means of evaluating  $L_m$ .

## 5-14. Mathematical Aids

a. Computer programs are available for most of the complex problems associated with lock operation. The four programs listed in Table 5-3 are applicable.

b. Database contents, H5300, are outlined in Appendix C. Computer input and output examples, H5310 and H5320, are included in Appendix F.

**Table 5-3**  
**CORPS Computer Programs for Lock Operation**

Program	Brief Title	Description
H5300	Database-Lock Studies	Reports (86) are being arranged in a database so that description (251 items) and measurement types can be printed. Database is being filled.
H5310	Surge in Canals	Surge characteristics (idealized as presented in EM 1110-2-1606) are evaluated. Program is fully operational.
H5320	Symmetrical Systems	Hydraulic characteristics (idealized as described in Item H2 are evaluated. Program is fully operational.
H5322	Symmetrical Systems (R2)	H5320 revised to accommodate distributed flow acceleration and hydraulic friction and roof expansions. Program is operational off CORPS.

*Section IV*  
*Culvert Features*

**5-15. Goals**

The importance of providing efficient hydraulic shapes for entrances, bends, expansions, contractions, etc., cannot be overemphasized. This is particularly important for components of hydraulic systems for locks with high lifts. Many existing locks have been designed without proper regard to efficient and smooth filling operations. However, modernization of obsolete projects introduces opportunities to design faster and more efficient system. In order to reduce the time required for lockage and still maintain safe operating conditions, the filling system is designed to provide equal distribution of flow into and out of chamber ports, to reduce surging and vortex action, and to provide culverts that are as hydraulically efficient as possible. The degree of refinement in the design of various units of the hydraulic system must be balanced by construction costs.

**5-16. Improved Performance**

Reduced operation time is achieved by streamlining the shape of the culverts and ports to reduce energy loss. Energy losses are reduced by having hydraulically smooth flow passages and rounded entrance corners on ports and conduits. Other aspects of improved performance also exist but are more difficult to evaluate. For example, proper distribution of the flow between manifold ports facilitates the dispersion and dissipation of jets issuing into the lock chamber or lower lock approach. In high-lift locks, streamlining for the elimination of excessive localized negative pressures and cavitation becomes increasingly important. Streamlining of the intake ports effects better flow distribution and reduces vortex action of the intake.

**5-17. Evaluation**

Although general criteria for the type and degree of streamlining that should be used for a given condition is not available, numerous examples can be found in model and prototype studies (Appendix C) that can be used for comparison. Corners should be sufficiently rounded to prevent separation of the flow from the boundaries. The angle of divergence in venturi-shaped ports should be small to avoid separation at the boundary.

*Section V*  
*Valve Hydraulic Characteristics*

**5-18. Design Concerns**

Valve characteristics are provided in EM 1110-2-1610. Items of particular concern for reverse tainter valves as addressed in EM 1110-2-1610 are

- a. Valve hoist loads.
- b. Valve siting (including submergence and air venting alternatives).
- c. Cavitation parameter evaluation.
- d. Valve shape and structural description.
- e. Valve lip details.
- f. Valve loss coefficients.
- g. Culvert roof pressure downstream from valves.



### 5-19. Valves With Expansions Downstream

a. Recent concerns (item 83) with the change in energy loss due to a roof expansion immediately downstream from the valve are summarized in Plates 5-1 through 5-3. The roof expands from a value  $B$  (Figure 5-4) to a value  $B_1$ . The valve loss coefficient is equivalent to an abrupt expansion from a maximum jet contraction,  $C_c b$  to an intermediate roof elevation  $B_1^*$ . The energy loss is greater with the expansion than with a horizontal roof. When the roof expansion begins more than 4.5  $B$  downstream from the valve, the valve and expansion are treated as separate form loss items.

b. For equal flow rates the pressure drop coefficient defined in Figure 5-5 is not measurably influenced by downstream expansion.

#### Section VI

#### Low Pressure Effects

### 5-20. General Concerns

Subatmospheric pressure permits air to enter the flow (see Section VII). The abrupt release of air into the chamber or valve wells can cause unsatisfactory lock operation. Vapor pressure, which is the extreme lower limit of subatmospheric pressure, is a major concern for high-lift locks. A separation zone (sharp bends, abrupt expansions, joints, etc.) will develop local cavitation for sufficiently high velocities and sufficiently low approach pressures. Incipient cavitation criteria are available for surface finishes, control devices, and flow passage variations (see HDC and items B1, B2, B3, B10, C1, M10, N1, and R7). Criteria based on data from alternate hydraulic structures, such as outlet works, are applicable to locks provided approach velocities and pressures are correctly evaluated.

### 5-21. Reverse Tainter Valves

Criteria for the assessment of cavitation potential are presented in Plate 5-4 of this document. Any conditions that allow a cavitation parameter ( $\sigma$ ) of less than 0.6 to develop is unacceptable. EM 1110-2-1610 addresses cavitation near reverse tainter valves at high-lift locks.

#### Section VII

#### Air Inflow and Outflow Devices

### 5-22. High-Lift Lock Air Vents

Valves for high-lift locks are commonly vented to preclude cavitation damage. Air vent design is presented in

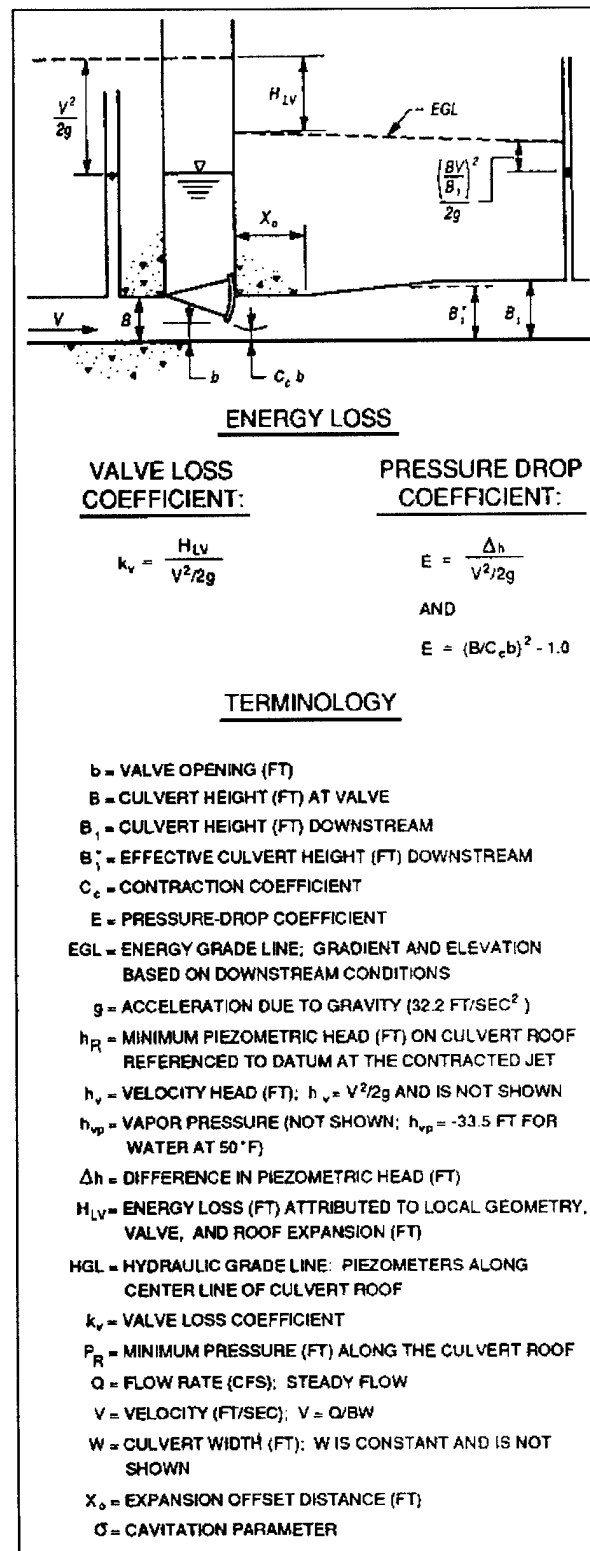
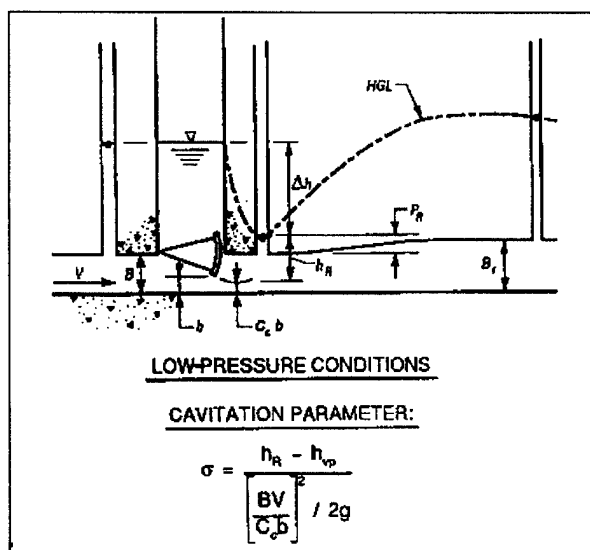


Figure 5-4. Valve loss coefficient (definition sketch)



**Figure 5-5. Definition sketch. Calculation of pressure at the culvert roof immediately downstream from the filling valve**

EM 1110-2-1610, EM 1110-2-1602, and HDC charts. Because of the potential adverse impact of air flow on chamber performance in the prototype lock and concerns regarding the minimum acceptable pressure below the operating valve, design practice is generally to oversize the air vent and establish a satisfactory orifice or air-valve setting to limit air flow. The orifice sizing or valve setting is established by observation in the prototype.

### 5-23. Low-Lift Lock Air Vents

Older low-lift locks with high culverts and normal tainter valves have required air release vents between valve and chamber. Occurrences in which large disruptive air bubbles entered these low-lift chambers have been noted. For high-velocity flows (high lifts) the air entering the chamber tends to be frothy and not disruptive to lock performance. For any design (or modification) requiring air outflow vents, the rising pressure gradient along a manifold culvert (items M5 and M10) and air flow characteristics (item F1) are of concern.

#### Section VIII

#### Vorticity at Intakes

### 5-24. General

An intake manifold will operate at its maximum efficiency only when the approach flow is free of

turbulence and vortices. Vortex formation lowers the efficiency of the manifold by diminishing the effective area of the openings and by introducing a component of velocity perpendicular to the direction of flow. Basic design procedures that will ensure vortex-free approach flow are not known, but model tests on intake manifolds have indicated methods of improving approach flow conditions. In model tests on intake manifolds located in the top of the upper sill, with the series of ports parallel to the upstream gate, vortex action was reduced by decreasing the distance between the manifold and the upper gate; increasing the space between ports; increasing the port area at the sill face; and increasing the port submergence. Vortices are less likely to occur during the accelerating flow of the valve opening period than in decelerating or steady flow. Vorticity is highly affected by local structures and channel geometries. Although precise scaling rules have not been established for these types of vortices, general guidance is to consider a surface swirl as acceptable whereas a depression (> 1/8 in. in the model) becomes questionable.

### 5-25. Evaluation

A larger entrance reduces intake losses, reduces the tendency to draw air into the intake, and reduces the chance of drift or ice damaging the racks by impact. By using several small intake openings instead of one large one, the flow is spread over a wide area; hence, the tendency for the formation of vortices and the suction of air into the culvert is further reduced. Enlargement of the intake and locating the top of the intake well below the minimum upper pool level ensures that the pressure gradient will be above the roof of the intake making it difficult to draw air into the culvert. The use of several small intake openings is also better structurally when the openings are located in a lock wall. Trashracks can also be kept to a reasonable size by the use of several small openings. When the intakes are located near to the upper pool level where floating drift or ice can easily reach them, the gross intake velocity is usually limited to 8 or 10 fps to avoid damage to the racks by impact.

#### Section IX

#### Energy Dissipation at Outlets

### 5-26. Conditions

Unfavorable navigation conditions, such as excessive turbulence and unusual velocity patterns, are the major problems to be considered when designing a discharge manifold in the lower approach. Scour near the outlet structure is an additional concern whenever the outlet is

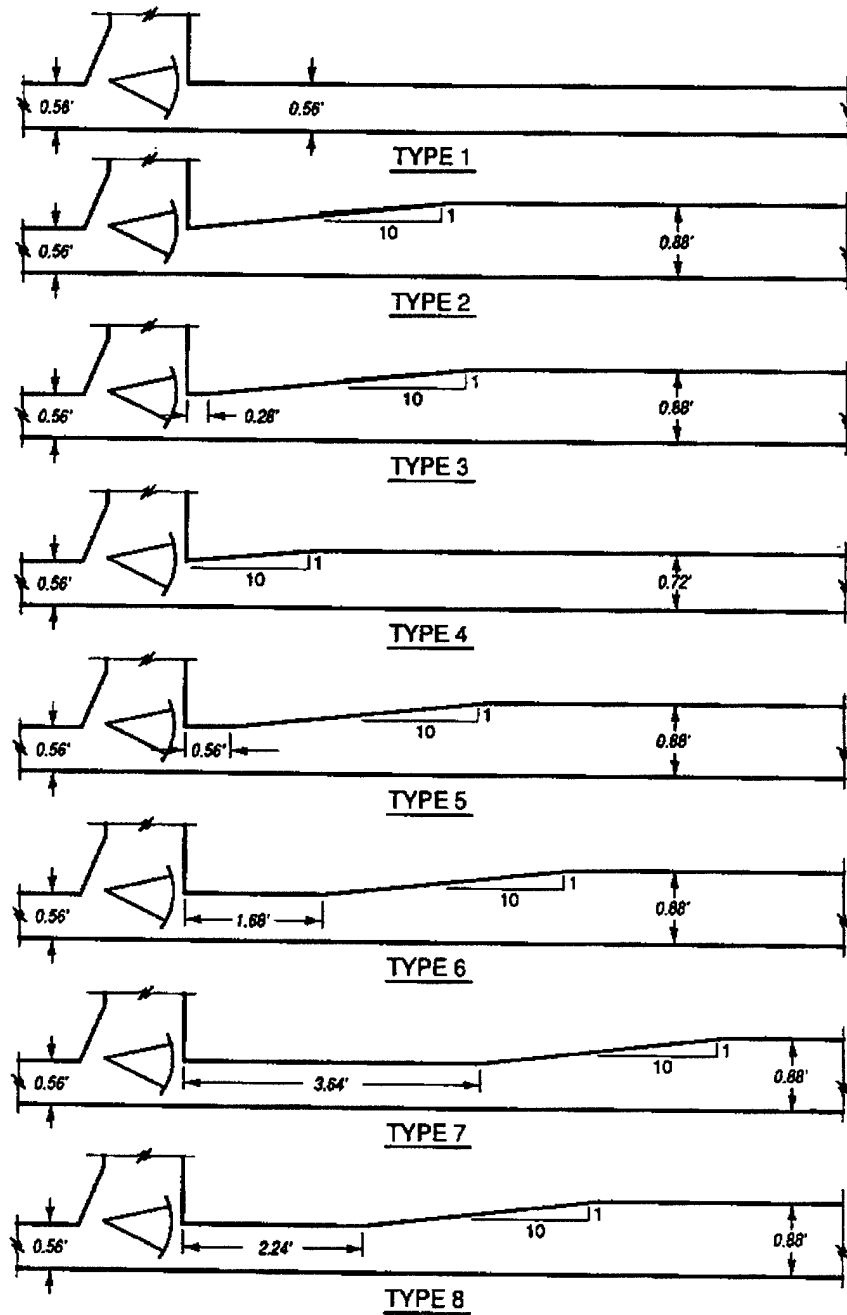
**30 Jun 95**

near an unprotected channel boundary. The discharge manifold is usually kept as short as possible to minimize cost. The cushion depth remains essentially the same throughout the locking operation.

#### **5-27. Options**

As discussed in paragraphs 4-19 and 4-20, discharge manifolds may empty all or part of the flow into the

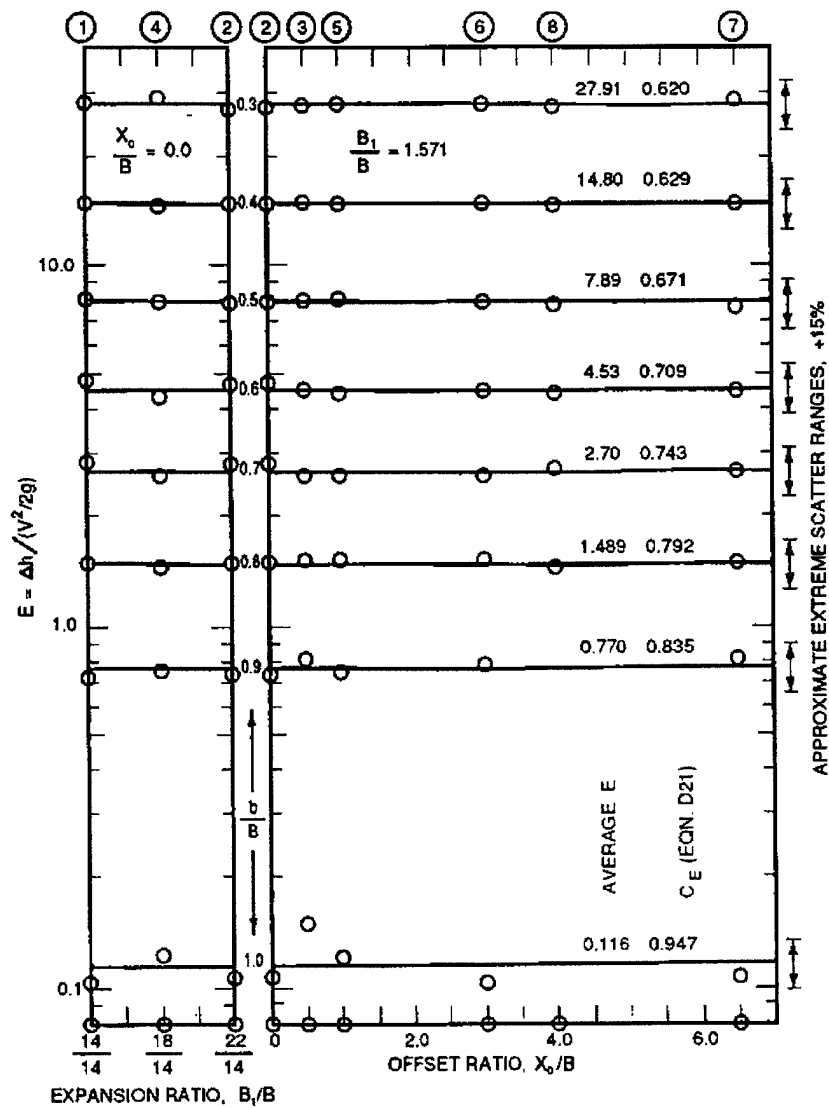
lower approach or into the river outside of the lower approach walls. When the total flow is discharged into the lower approach, the expansion in port area may have to be quite large to obtain low outlet velocities. The outlet location is normally not a factor (other than with regard to overfill and overempty) in chamber performance.



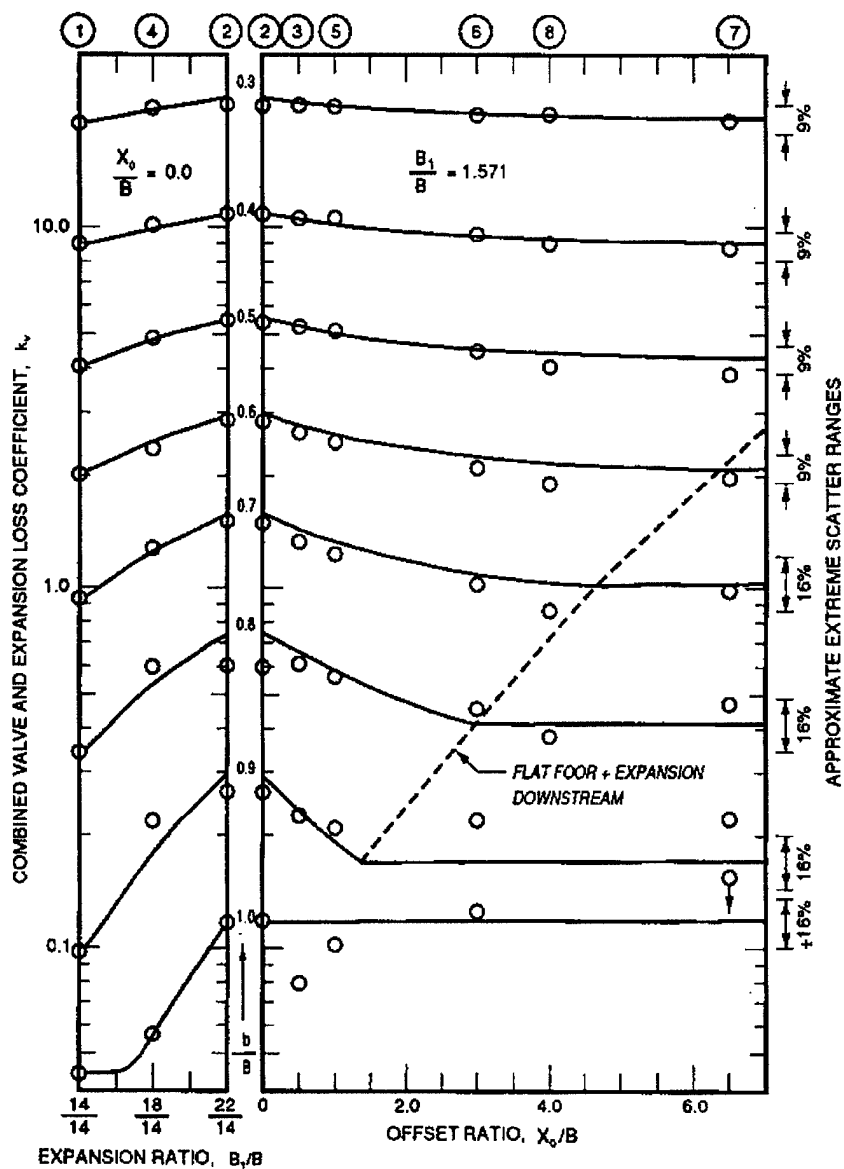
FROM ITEM 83

TYPE OF CULVERT ROOF  
EXPANSIONS USED IN  
LABORATORY STUDY

Plate 5-1



PRESSURE DROP COEFFICIENTS



VALVE-AND-EXPANSION  
LOSS COEFFICIENT

Plate 5-3

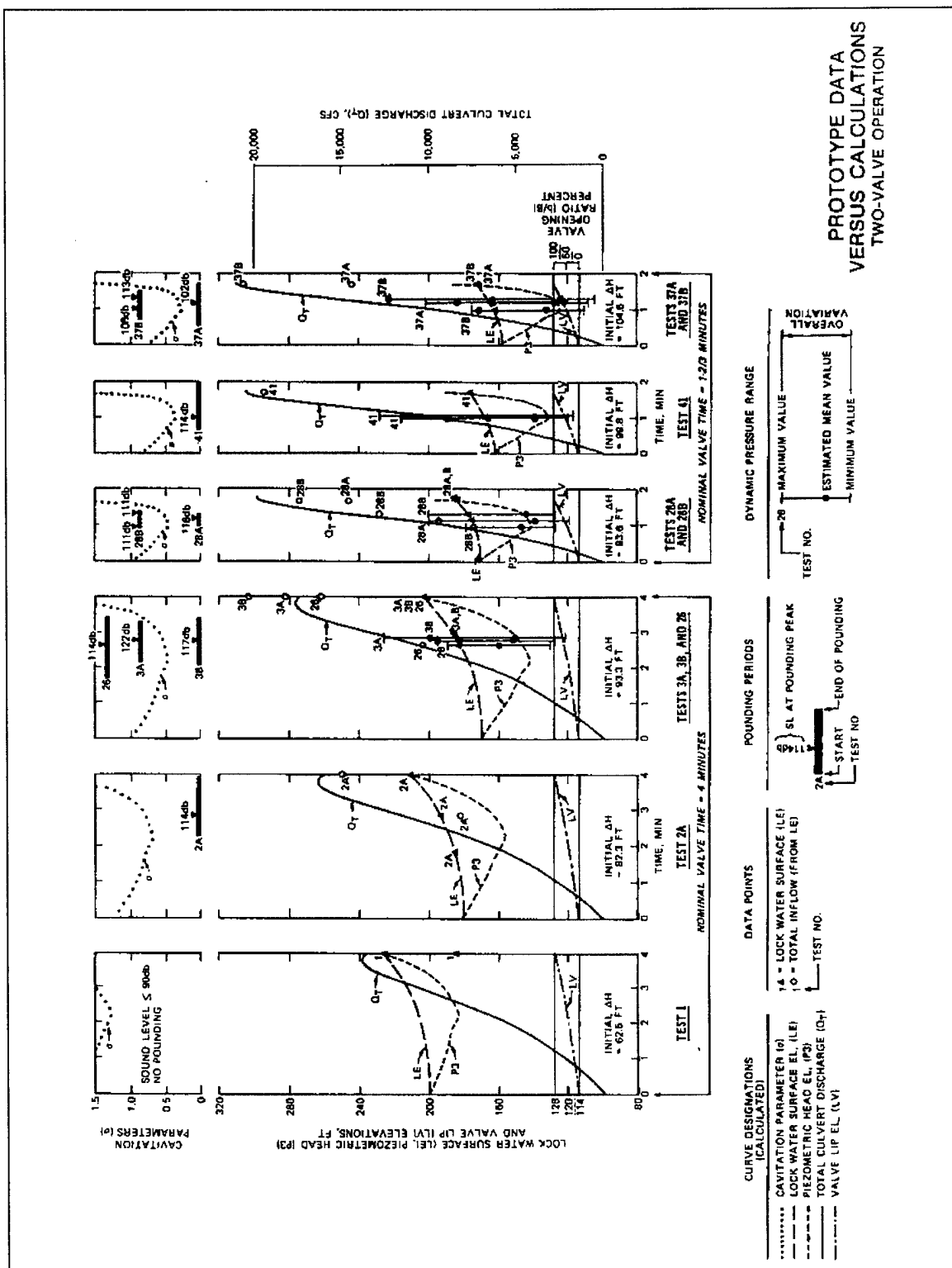


Plate 5-4

## Chapter 6

### Hydraulic Model Studies

#### Section I

#### Introduction

#### 6-1. General

Laboratory studies have significantly improved the efficiency of lock filling-and-emptying systems. They have reduced lockage times and mitigated many conditions that have been hazardous to both traffic and structures. Prototype studies have verified and added to the data obtained from these model studies.

#### 6-2. Purpose of Model Study

Data for the design of a filling-and-emptying system for a low-lift lock are available. However, if the filling-and-emptying system under consideration varies from conventional types, a thorough study using a hydraulic model may be necessary. A lock with a lift of 40 ft or more generally departs from conventional designs, and normally cannot be confidently patterned after other designs.

Even though problems are not apparent, a model study usually brings to light corrections or improvements in design that result in smoother and faster operation and effects savings in construction and maintenance costs. Flow conditions in locks with lifts of 100 ft or more, require model studies and other specialized laboratory studies during early stages of the design process.

#### 6-3. Scales

The most satisfactory scale ratios have been found to range from about 3:100 to 6:100. These scale ratios permit visual observations of turbulence and other flow conditions and permit the use of usual types of laboratory instruments for making measurements of pressures, velocities, discharges, and linear dimensions. A 1:25 scale predominates for recent lock studies.

#### 6-4. Model and Prototype Similarities

Models must be geometrically and, to the extent possible, dynamically similar to the prototype. The common dimensional relationships applied to lock models are listed in Table 6-1.

**Table 6-1**  
**Model and Prototype Dimensional Relationships**

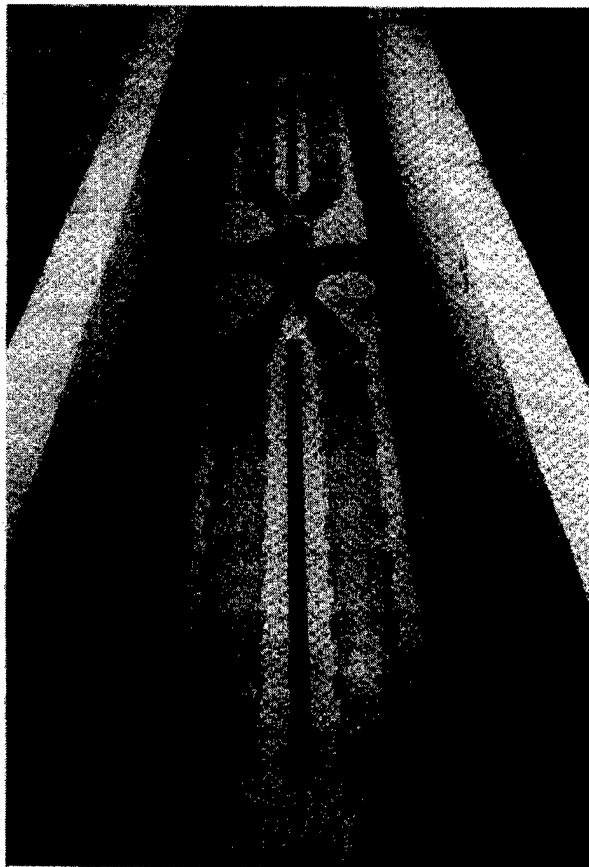
Quantity	Dimension	Symbol	Scale Relationship
Scale relationship	$L_m/L_p$	$r$	—
Length	ft	$L$	$r$
Head, lift	ft	$h, H$	$r$
Area	$\text{ft}^2$	$A$	$r^2$
Volume	$\text{ft}^3$	$L^3$	$r^3$
Velocity	ft/sec	$V, v$	$r^{0.5}$
Time	min or sec	$t$	$r^{0.5}$
Discharge	cfs	$Q$	$r^{2.5}$
Force	lb	$F$	$r^3$



30 Jun 95

### 6-5. Model Construction

Construction materials used for lock models include metal, concrete, plastics, and wood. Transparent plastics are used for sections of conduit where observations of the interior flow conditions are desired and for forming curved surfaces such as entrances, bends, or dividing vanes. Where duplicate parts are required, such as lock chamber ports, lateral entrances, floor laterals, etc., it has been found that accurate reproductions can be made in concrete by the use of wooden forms. Swelling or contraction, which are objectionable features of wood, is not experienced with concrete. Materials for the various parts of the model structure should be selected on the basis of their resistance to dimensional change, particularly those sections and surfaces that are exposed to flow or changing volumes of water. The new Bonneville Lock Model is shown in Figure 6-1.



**Figure 6-1. Hydraulic model of New Bonneville Lock.** The following materials are generally used: chamber, marine grade plywood; culverts, manifolds, valve wells, Plexiglas; valves, bronze plate

### 6-6. Instrumentation

Because of the variable flow conditions in a lock model and because these conditions change quite rapidly, it is essential to have an automatic method for recording most phenomena. Electronic transrecorders, digitizers, etc., have been developed that record and process automatically the following types of data:

- a. Elevation of upper pool level (initial value, draw-down, etc.).
- b. Elevation of lower pool level (initial value, swell, etc.).
- c. Movement of culvert filling (or emptying) valve.
- d. Elevation of water surface at required locations in the lock chamber.
- e. Pressures at various points in the hydraulic system by means of piezometers, particularly among curved surfaces; at turns, contractions, and expansions; along the culverts; and at the control valves.
- f. Longitudinal and transverse forces acting on vessels in the lock chamber (see Figure 6-2).
- g. Rate of flow of water into the lock chamber (normally obtained from item *d* above).
- h. Time synchronization to within about 2 sec (prototype scale); normally to about 0.4 sec, model scale (1:25 model).
- i. An event signal that can be operated manually to indicate occurrence of special events such as the taking of photographs during an operation, etc.

### 6-7. Pressure Measurements

Piezometers recording pressures may be connected by flexible tubing to transparent glass or plastic tubes mounted on a manometer panel board rather than automatically read. These pressures can be read visually on the individual manometers or photographed as a group for later reading and interpretation. Only the latter method is feasible in a regular test where flow conditions are continually changing. Some lag in the readings occurs depending upon the diameter and length of the connecting tubing as well as on the rate of actual

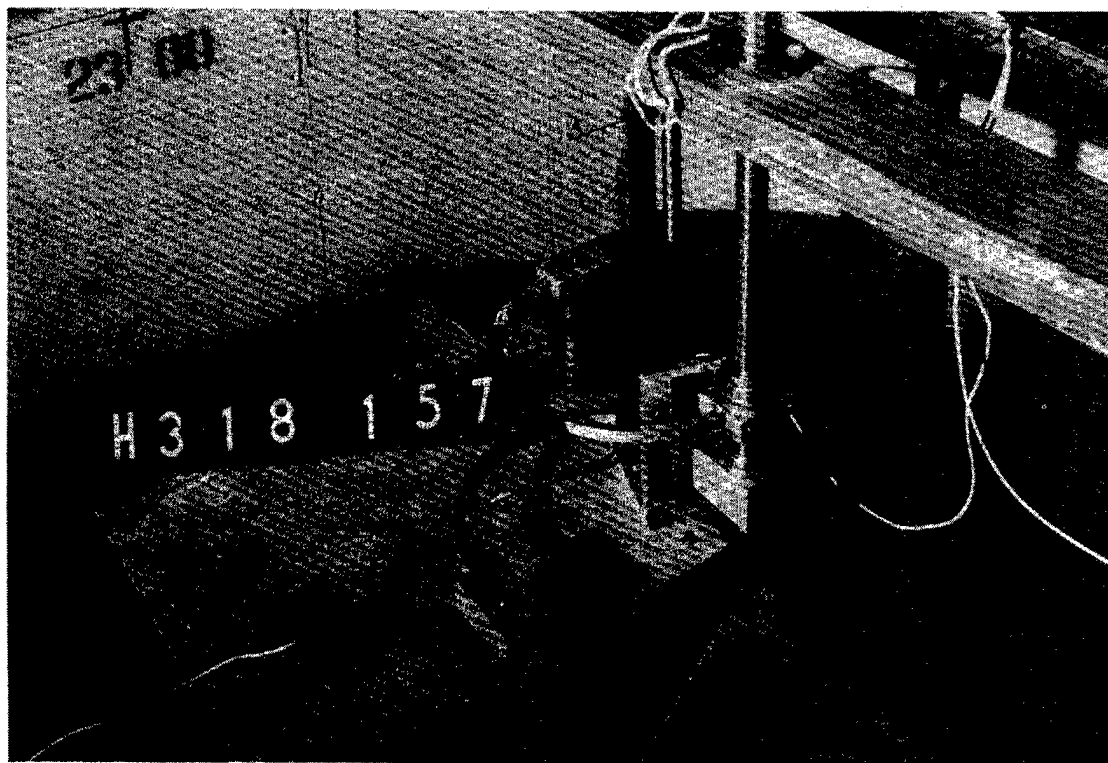


Figure 6-2. Hawser force measuring devices

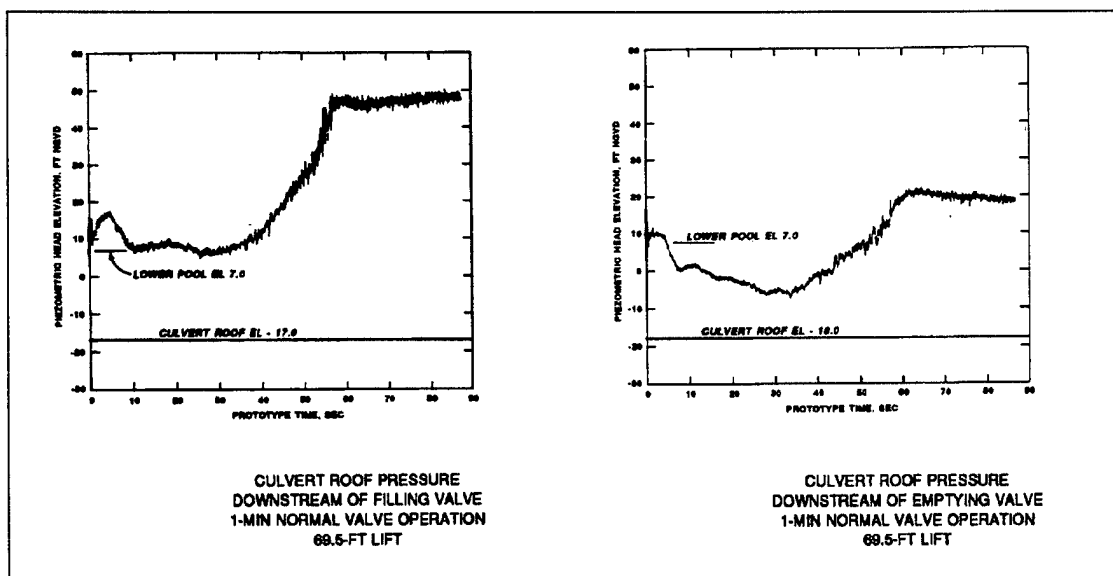


Figure 6-3. Dynamic pressure measurements

pressure change. Steady-flow tests are frequently made to permit more accurate observation of flow and head loss conditions in the system. Flow distribution in manifolds is usually determined using a pitot tube or other small flow-metering device under steady-flow conditions. Where rapid pressure fluctuations occur and cavitation or excessive negative pressures are suspected, the region in question should be investigated by means of surface-mounted electronic pressure cells. Areas of this nature may exist on the downstream face of control valves, culvert surfaces below valves, entrances to inlets, and at gate or bulkhead slots. An example measurement is shown in Figure 6-3.

## Section II Prototype Expectations

### 6-8. General

A prototype lock filling-and-emptying system is normally more efficient than predicted by its model (paragraph 6-3). The difference in efficiency is acceptable as far as most of the modeled quantities are concerned (hawser forces, for example) and can be accommodated empirically for others (filling time and overtravel, specifically). However, in circumstances in which knowledge of extreme pressures within the culverts in the prototype is important, additional corrections to the predictions from the model are required. These corrections are particularly important for high-lift locks in which questions regarding cavitation (resulting from extremely low pressures) are of concern.

### 6-9. Revisions to Scaled Values

Adjustments to model-based coefficients for prototype application are based on one of the following three general approaches.

*a. Filling-and-emptying times.* General guidance is that the operation time with rapid valving should be

reduced from the model values by about 10 percent for small locks (600 ft or less) with short culverts; about 15 percent for small locks with longer, more complex culvert systems; and about 20 percent for small locks (Lower Granite, for example) or large locks having extremely long culvert systems. Although these values are approximate, the resulting  $C_L$  value is a reasonable estimate of discharge coefficient  $C$ , which in turn provides a reasonable basis for evaluating a prototype  $k$  value (see Chapter 5).

*b. Similar (model and prototype) locks.* A lock as similar as possible to the design lock and for which either operation time or culvert pressure data are available (model and prototype) provides a comparison such as in *a* above, or for pressure values, direct evaluation of prototype loss coefficient values.

*c. Reynolds number corrections.* Boundary friction differences, assuming smooth boundaries in both model and prototype, explain about one-half of the efficiency change with regard to operation time for certain locks (Lower Granite, for example). The remaining change is due to undeterminable variations in form coefficients or the Reynolds number difference. Sensitivity analysis (systematic variations in individual form coefficients) permits extreme conditions to be accounted for in design.

## Section III CE-Sponsored Hydraulic Model and Prototype Studies

### 6-10. Database

The database, H5300, contents are summarized in Appendix C. The database is being filled to ultimately include the 86 reports and 251 features studied by WES, Bonneville Hydraulics Laboratory, and the St. Paul District as described in Appendix C.

## Chapter 7 Other Hydraulic Design Features

### 7-1. Scope

Hydraulics design features not directly related to the hydraulic filling-and-emptying system are discussed in the following sections.

#### *Section I* *Surge Reduction*

### 7-2. Solutions

Surge reduction is accomplished by:

*a.* Slower filling-and-emptying systems or longer valving. This results in lower surges at the expense of long operation time.

*b.* Surge basins to suppress the rapid drawdown (filling) or upwelling (emptying) during the normally brief period of rapid change in discharge rate.

*c.* Hydraulic surge control methods as a means of removing or adding water to a small canal located between two locks. Additional volume is needed during filling of the lower lock; removal is needed during emptying upstream.

*d.* Staged lifts to reduce peak flow rates (as in *a* above) at substantial increase in operation time.

*e.* Broad approach channels to lower surges; i.e., canalized systems are more susceptible to surge effects than are broad river systems.

### 7-3. Computational Aids

Surge reduction is discussed in EM 1110-2-1606. Surge height calculations as presented in EM 1110-2-1606 are computer accessible in the CORPS program library (H5310). An example input/output is presented in Appendix F. For long canals or more complex geometries, study aids such as more comprehensive analytical (computer-based) solutions or physical model studies are needed.

#### *Section II* *Impact Barriers*

### 7-4. Purpose

The purpose of a barrier is to provide an energy-absorbing device for barge tows to prevent damage to the gates in the event of a collision. Four such devices have been considered for use to protect lower miter gates. They are wire rope fenders, steel collision barriers, concrete collision barriers, and rope system impact barriers. The rope system impact barrier has been studied for use upstream of upper miter gates (the other three types appear less suitable for upstream use). These barriers are discussed in EM 1110-2-2602.

#### *Section III* *Water Saving*

### 7-5. Water Supply

During periods of low water on canalized waterways, a sufficient supply of water is required to maintain all navigation pools at or above planned normal pool elevations. The following factors affect pool elevation:

*a.* Available hydrologic water supply.

*b.* Leakage, seepage, and multipurpose (hydroelectric plant, for example) consumption.

*c.* Water requirements for lockages.

*d.* Pumpage or diversion, and return flow (where applicable).

*e.* Evaporation.

The water supply must be equal to or exceed the algebraic sum of the other factors in order to maintain the navigation pools. The water supply may consist of the natural flow of the stream, the supply furnished by storage reservoirs, or a combination of the two. A thorough investigation should be made for all items when any doubt exists as to the adequacy of the water supply.

## 7-6. Design Needs

Low-flow lock operation is an overall project concern that places site-specific conditions on hydraulic design. Such factors as operational procedures, canal surges and approach conditions, valve siting, etc., designed for normal conditions may not be suited for low flows.

### Section IV Dewatering

## 7-7. Concerns

Hydraulic concerns during dewatering include the following:

- a. Bulkhead locations.
- b. Pumping facilities.
- c. Outflow conditions.

## 7-8. Coordination

Dewatering exerts an extreme static loading on structural elements and requires specific considerations during lock structural detail design (see EM 1110-2-2703 and EM 1110-2-2602). Structures used for emergency closure are normally suitable for dewatering (item B5).

### Section V Emergency Closure

## 7-9. General Emergency Situations

Emergency situations occur at navigation locks when a lock gate becomes inoperative in an open or partially open position while a head differential exists between the chamber and upper or lower pool. Although the cause may be mechanical failure, the more frequent cause is a navigation error that holds the gate partially open. Although no universally accepted definition of *emergency closure* exists, the required action is generally understood to be that a closure structure must be rapidly placed in flowing water under head differential.

## 7-10. Consequences of Pool Loss

The main consequences of upper pool loss *downstream* of the project are due to the flood wave. Hazardous navigation conditions and rapid flooding of riverfront property are extreme possibilities. A less severe flood wave will commonly interfere with the operation of

private and commercial boat docks. *Upstream* impacts of pool loss include the following:

a. Economic and safety problems occur at commercial and recreational boat terminals. Long periods of navigation suspension have a severe adverse impact on the economy of an entire region. The primary loss on major navigating systems is loss of navigation channel.

b. In many areas, small riverfront communities depend on the maintenance of normal pool for water supply. Loss of pool during low-flow periods causes inconvenience and, possibly, health and fire hazards.

c. Rapid loss of pool and resulting drawdown causes bank instability. This problem is especially severe where important structures, highways, or railroads are located in the reach of instability.

d. A navigation project that includes hydropower loses some or all of its power-generating capability in case of upper pool loss.

e. Upstream pool loss causes a severe and adverse impact on fish and wildlife.

f. Upstream pool loss affects other site-specific factors particularly during extremely low upper pools.

## 7-11. Preliminary Studies

In the design of most modern navigation lock and dam structures, emergency closures have been provided.

## 7-12. Types of Closure Systems

A broad range of structures are in place as emergency closure devices at existing CE locks. Operational and economic considerations, rather than purely function, limit the choices for new designs. Structural details are available in EM 1110-2-2703 and in other references (item B5, for example). Examples of the more common closure devices are as follows:

### a. Bulkheads.

(1) The most common type of emergency closure for locks and spillway gate bays is a bulkhead consisting of one or more sections and commonly constructed of welded, high-strength steel. A watertight skin plate is generally provided on the upstream side. Top and bottom seals, side seals, and roller assemblies complete the

structure. The roller assemblies bear on bearing plates constructed in pier or lock wall recesses. The vertical height of the structure may vary from 3 to 12 ft depending on design constraints of a specific project. Several individual units are usually required for complete lock or dam closure.

(2) Most designs do not permit water flowing over and under the bulkhead units during lowering. Stacking units may be required for successful placement. Some bulkheads are equipped with an overflow plate attached to the top truss. The purpose of such design is to utilize bulkheads for flushing ice and debris, when necessary. If bulkheads are designed for placement in flowing water, hydraulic model studies of previously untested situations are needed.

(3) The units are either stored at the locks or retained in dogged position over the dam. In the former case, an overhead gantry crane is used to transport the individual units to the lock. The first unit is dogged over the bay or the lock and the next unit is moved from storage, latched to the first one, and then the assembly is lowered and dogged a second time. Additional bulkhead units are latched to the assembly until closure is achieved.

(4) Another method of placement uses a stiff-leg derrick positioned at the lock. The derrick raises and places individual units in bulkhead recesses. Additional units are added until closure is achieved. During lowering, the assembly is held in place by a stop log carriage.

*b. Vertical lift gates.*

(1) Emergency lift gates are either the single-leaf or the double-leaf type (see EM 1110-2-2703). The cost of the gate, storage arrangements, and hoist mechanisms for either type vary according to river stage and project (closure) lift. Economic studies are ultimately used to choose between single- or double-leaf gates. Double-leaf vertical lift gates have been constructed at several navigation locks on the Ohio River navigation system; other navigation systems use single-leaf vertical lift gates. In either system the gates are stored in submerged position under the lock emergency sill upstream of the upper miter gates. The double-leaf construction permits the utilization of locks as floodways when the river stage prohibits navigation. An emergency-closure single-leaf gate is illustrated in Plate 7-1.

(2) For the double-leaf type of design used in the Ohio River navigation system, only the downstream leaf is designed to permit closure in flowing water. However, the vertical height of one leaf is sufficient to effect closure under unbalanced head (flowing water) up to normal pool level. Should closure be required for stages above normal pool, then both leaves can be raised, since upstream and downstream heads are balanced. The operation of double-leaf-type emergency closure is shown in EM 1110-2-2703. For the single-leaf emergency gate, provisions must be made in the design to allow closure.

*c. Upstream emergency dam.* A type of emergency closure designed and constructed by the U.S. Army Engineer District, Nashville, for several locks on the Cumberland River navigation system is an emergency dam. This consists of several wickets that remain submerged on the floor of the emergency sill during normal locking operation, but they are raised into position during emergency conditions. Each wicket is raised individually by means of a chain hoist, sheaves, and a winch located on the top of the lock wall. When wicket No. 1 is in the lowered position, the landward hoist chain fits into a recess in the lock wall. As the first wicket is raised, it also raises the attached hoist chain of the next wicket. After locking the first wicket in position, the sheave is passed over to the riverward side and the second wicket is raised, which also raises the hoist chain for the third wicket. The operation continues in this manner until all wickets are raised. Similar closures have been constructed and operated on other navigation systems. In the original design, the wickets were constructed with flat skin plate; however, hydraulic model testing includes a curved skin plate.

*d. Other systems.*

(1) Stop logs, commonly consisting of wooden beams, can be placed in recesses upstream of spillway gates or lock miter gates using a hoisting mechanism. However, in general, operating heads on the dam usually must be reduced before placement. Since this arrangement would result in partial or total loss of pool, they cannot be considered a true emergency closure. Bulkheads, described in *a* above, are sometimes designated as stop logs. An older type of emergency closure is used for the auxiliary lock at McAlpine Lock and Dam on the Ohio River system. This type of closure includes a separate horizontal beam placed across the top of the lock walls with a derrick. Closure panels are vertically placed between the beam and the concrete sill to complete the closure operation.

(2) Submergible tainter gates are another alternate for emergency closure. Under normal operating conditions, the gates rest in a recess built in the emergency sill, upstream of the upper miter gates. During emergency closure, the gates are lifted to position by cables. Provisions must be made to clean the gate recess periodically to free it of accumulated silt and debris.

### 7-13. Design Loadings

An overview of design loadings (EM 1110-2-2703) is as follows.

*a.* Hydrodynamic forces result from the water flowing under the emergency closures. On emergency bulkheads, these forces can result in hydraulic uplift or downpull depending on the design. In order to lower bulkheads in flowing water, the uplift force must be less than the submerged weight of the bulkhead. Knowledge of the magnitude of hydraulic downpull is important for the design of the hoisting machinery. Overflow and underflow on emergency bulkheads are undesirable from the standpoint of hydrodynamic forces and should not be used. Hydraulic model studies are sometimes required to determine forces for a particular design.

*b.* The weight of the bulkhead is to be determined in the usual manner considering the structural elements and members of the closure. The majority of the bulkheads are of structural steel, but aluminum bulkheads have been used. The submerged weight is important in considering the ability to lower the closure structure in flowing water.

*c.* Frictional forces develop along the side support of closure structures. The magnitude of these forces depends on the type of bearings and side seals as well as on other loadings (*a* and *b* above, for example). Reference is made to EM 1110-2-2703 for details.

*d.* Some types of emergency closure systems, notably vertical lift gates, can be used in a dual role serving also as lock gates. Barge impact loads are considered for these designs. Reference is made to EM 1110-2-2703 for the magnitude of such loads.

*e.* Ice forces are considered, depending on the climatic condition at the location of the closure (see Section VI).

## Section VI

### Ice Control at Locks

### 7-14. Types of Ice

Ice in and around locks has always been a nuisance. Most lock operators have worked through the winter season using pike poles and steam to combat ice. Some locks, especially in more severe climates, simply close. However, recent interest in year-round navigation has led to closer identification of winter lock-operating problems and development of potential solutions to these problems. Three kinds of ice create problems for navigation: sheet ice, brash ice, and frazil ice. Sheet ice is a continuous cover of more or less equal thickness. Brash ice is an accumulation of ice fragments up to above 6 ft in the longest dimension that can pack to depths greater than the normal ice thickness. Frazil ice is an accumulation of small plates and spicules formed in turbulent water that often adheres to trashracks, gates, intakes, and other structures in the water. EM 1110-2-1612 gives additional background information and details of ice control measures.

### 7-15. Ice Problems

Ice problems at navigation locks are caused primarily by brash ice floating downstream or being pushed ahead of downbound traffic. The floating pieces of ice hinder gate opening and closing, stick to lock walls creating problems with vessel passage, and stick to lock gates causing operational problems. Large quantities of ice pushed ahead of a downbound ship can interfere with lock operation because a separate lock cycle solely for ice is often required by long ships using short locks. If ice could be prevented from entering the locks, most of these problems would not occur.

### 7-16. Air Screen

*a.* An air screen can keep ice from entering a lock. When large volumes of compressed air are released at depth across a channel, a high upstream and downstream surface water velocity is created that precludes the passage of ice or debris. This type of installation is called an air screen, and an application at Sault Ste. Marie has demonstrated its effectiveness. Air screens should be located between the upstream ends of the guide wall and

guard wall; when placed closer to the lock, any ice pushed into the lock approach has nowhere to go and will accumulate. This same principle has been used successfully either as a single, point-source bubbler or as a line bubbler to keep ice out of miter gate recesses, allowing them to open fully.

b. An air screen was installed at the upper approach to the Poe Lock on the downstream, vertical face of an emergency stop log gate sill. The sill is located about 200 ft upstream of the lock gates. The riser line was installed in the stop log recess in the wall. The width of the lock at this point is 110 ft and the height from the top of the sill to the top of the lock wall is 39.2 ft. The manifold line was installed at a depth of 34.5 ft in December 1977 and was preassembled into four sections: two sections 27.75 ft long and two sections 24.5 ft long. Union connections joined the sections. The riser was assembled in one 38.5-ft section. The sections were light in weight; two to three people were able to move them by hand. All equipment for a hardhat diver and the preassembled pipes were placed on a 100-ft barge that served as the working platform. The barge was positioned above the sill, and sections were lowered on ropes to the diver below who made the union connections and strapped the line to the concrete sill. One flexible hose coupling, from the diffuser to the riser, was also made underwater. The above-water installation process consisted of simply connecting a 50-ft flexible hose from the top of the riser line to a rented compressor. A 10,000-gallon fuel tank was placed beside the compressor to supply fuel.

c. The air screen was put into operation on 12 January 1978 when ice started to cause problems with lock operations. It was continuously available for service until 30 April 1978, except for a 5-day repair period in late March. By 1 May ice no longer caused problems requiring the air screen, and the rented compressor was returned. During the 104 days of operation, the total running time on the compressor was 754 hr. Total fuel consumption of No. 1 fuel oil was about 7,750 gallons. The air screen has demonstrated that it can hold back ice pushed ahead of downbound traffic. With ships in the 70-ft beam class, the ice was held back until the bow entered the air stream. The stream was not as effective with the wider 105-ft beam ships. Once the bow passes the nose pier about 130 ft upstream of the screen, the approach is just a little over 110 ft wide; so most of the ice remaining in the track is pushed into the lock. The problem might be solved by relocating the air screen upstream of the nose pier area and by providing some area for the ice to be pushed outside the vessel track.

The merits of the air screen cited by lock operating personnel, besides the reduction in vessel lockage time, were savings in wear and tear on the lock gate and operating mechanisms and savings in time and effort required to remove ice collar buildup on the lock walls.

#### 7-17. Lock Wall De-icing

Ice buildup on lock walls occurs throughout the winter and presents no problems until it covers mooring bits or becomes so thick that the lock is effectively too narrow to admit vessels. If the lock is normally kept at low pool elevation, the lock walls cool to ambient temperature and upon filling are coated with a glaze of ice. Since this ice coat can continue to build (like dipping a candle) locks are normally kept nearly full during winter operations. When entering ships push ice into the lock, especially downbound, ice is often crushed against and adheres to the lock wall, exacerbating the problem. On rivers the standardization of barge width and the barges' square bows minimize this difficulty, but other locks such as those in the Great Lakes connecting channels can have severe problems.

a. *Ice cutting saw.* The U.S. Army Cold Regions Research and Engineering Laboratory designed and assembled a mechanical cutting system to remove the ice collars. The device consists of two parts: the cutting system and the drive and propulsion unit. The drive and propulsion unit is a 65-horsepower, four-wheel-drive tractor, originally manufactured as a trencher (the tractor can be purchased without the trencher attachment). The drive line for the trencher was modified to accommodate the cutting system by extending the drive shaft and attaching a drive sprocket to its end. While in the cutting mode, the engine powers the shaft and sprocket directly and the drive wheels indirectly through a separate hydraulic drive system so cutting power and propulsion power can be independently controlled. The cutting system is one used in the coal industry. It consists of a rugged bar and chain with cutting bits attached. The bar is 9.5 in. wide to the chain guide, 1.5 in. thick, and 15.9 ft long and is attached to the drive shaft housing. Movement of the bar is hydraulically controlled. Different kerf and bar thicknesses have been used, but earlier tests showed that a narrow logging saw was too flexible. The bar is grooved to accommodate the sprocket-driven chain and cutting bits and has a roller nose tip to reduce friction and wear. Chain tension is controlled by a high-pressure hydraulic cylinder capable of exerting 1,800 lb/ft at 10,000 lb/square inch (sq in.). The bar and chain hang about 30 in. past the side of the tractor and the drive wheels.



*b. Operation of the ice cutting saw.* When a problem ice collar has built up, the esplanade along the lock wall is cleared of snow. The tractor is then positioned with the right wheels close to the curbing along the wall so that there is about 1.5 in. of clearance between the wall and the bar and chain. A spacer on the wall side of the bar prevents the cutters from damaging the wall. A guide marker located off the right front wheel is positioned and set so the driver can maintain the proper position by keeping the marker and the reference point (top of curb) aligned. Looked at from the driver's point of view, the chain rotates clockwise with the tension cutting side on top of the bar. To start a slot for the bar, the underside of the saw is used until the tip cuts completely through the collar. The slot is cut with the tractor stationary. Once a slot is cut through, the bar is placed in a forward position about 70 deg from the horizontal. Full throttle operation in third gear produces a chain speed of 380 ft per min, although chain speeds of up to 510 ft per min are possible in fourth gear. A traverse speed of over 10 ft per min can be maintained while cutting ice collars 6 to 8 ft deep by operating the transmission in third gear at full throttle.

*c. Copolymer coating.* A chemical coating that reduces the adhesive force between the coated surface and the ice can also help solve icing problems, although the ideal material would prevent ice formation altogether. The coating that was developed does not prevent ice formation, but makes removal of ice from coated surfaces much easier. The basic material is a long chain copolymer compound made up of polycarbonates and polysiloxanes. The copolymer coating should not be applied to a concrete surface unless it is certain that the concrete behind the coating can resist frost action in a critically saturated condition. Proper application guidance for surface coatings to concrete can be found in EM 1110-2-2002.

*d. Heating lock walls.* Intermittent heating of the lock wall to release ice is probably the best solution. One lock has been retrofitted with electric heat tape installed in saw cuts; however, this is a time-consuming and expensive operation. Before new construction or rehabilitation of locks, options for lock wall heating should be investigated.

#### **7-18. Lock Gate and Valve De-icing**

The operating machinery for filling and emptying valves has been reported to have icing problems, but little is known beyond the verbal reports from specific lockmasters. Thought should be given to minimizing direct

exposure to the atmosphere. Lock gates, especially the lower gate, should be insulated on their downstream side to minimize ice buildup on the upstream side that would make full opening of the lock impossible. On most existing gates, the downstream side of the gate is open, and while passing through the lock, ships push ice between the supports of the gate. To minimize this problem, gates should have a cover skin on the downstream side extending some 3 ft above and 6 ft below pool operating levels.

#### **7-19. Considerations for Rehabilitation and New Construction**

Whenever lock rehabilitation or new construction is considered, a number of ice-related concepts should be evaluated. Air screen and lock wall de-icing schemes have been covered in earlier paragraphs. The location of the filling intake should be situated so that filling currents do not pull ice into the lock approach. An ice and debris bypass should be considered whenever the approach channel is longer than a few hundred feet. Gate design should include insulation and a double skin to prevent ice from adding too much weight. Lastly, consideration should be given to a modified filling system that would add water to the upper end of the lock only. This would shorten the time required to flush the lock clear of ice and could be used as an emergency method of getting a disabled or burning vessel out of the locks.

#### *Section VII* *Repair and Rehabilitation*

#### **7-20. Purpose and Scope**

Major rehabilitation includes work that is non-recurring in nature and is intended to either increase the reliability of deteriorated features or increase efficiency, or shall not consist of routine or deferred maintenance, which will continue to be considered in the U.S. Army Corps of Engineers Operation and Maintenance General budget appropriations.

#### **7-21. Reliability Improvement**

*a.* Rehabilitation for reliability is major project feature restoration consisting of structural work on a feature of the lock which is intended to improve reliability the result of which will be a deferral of capital expenditures to replace the structure.

*b.* Rehabilitation is considered as an alternative when it can significantly extend the physical life of the feature

and can be economically justified by benefit-cost analysis. The benefit-cost analysis is a product of a risk analysis which combines probability of unsatisfactory performance with consequences. The work will extend over at least two full construction seasons and will require a specified threshold cost to be exceeded. This amount is specified in the annual Major Rehabilitation Guidance Memorandum. Additional guidance for the major rehabilitation program and the associated reliability analysis is found in ETL 1110-2-532.

#### 7-22. Efficiency Improvement

Rehabilitation for efficiency improvement is intended to enhance operational efficiency of major project components and increase outputs beyond their original project design. Threshold limits on a component that does not exhibit reliability problems is also specified in the annual Major Rehabilitation Guidance Memorandum. Efficiency items include the following:

- a. Modern machinery.
- b. Modern electrical equipment.
- c. Remote controls.
- d. Television surveillance system.
- e. Floating mooring bits.
- f. Tow haulage units.
- g. Lock wall extensions.
- h. Emergency closure system.
- i. Lock gate impact barrier.
- j. Improved filling system.

#### 7-23. Threshold Amounts

The threshold amounts listed for the reliability and efficiency improvement categories are adjusted annually

according to the Administration's economic assumption published each year as guidance in the Annual Program and Budget Request for Civil Works Activities Corps of Engineers.

#### 7-24. Typical Study Items

The following are common items to consider for major navigation dam rehabilitation projects:

*a. Dam stability.*

(1) Replace upstream and downstream scour protection.

(2) Install tendons through structure into foundation.

*b. Navigation improvement.*

(1) Move lock guide/guard walls.

(2) Change approaches.

(3) Change approach currents with training structures.

*c. Ice and debris control.* Install the following:

(1) Lock wall de-icer.

(2) Lock gate de-icer.

(3) Control booms.

(4) Air screens.

*d. Replacement in kind.*

(1) Resurface concrete surfaces.

(2) Repair or replace gates.

(3) Fix gate anchorages.

(4) Replace imbedded metal.

*Section VIII*  
*Environmental Concerns*

**7-25. Effect of Lock**

The massive character of a navigation lock suggests that environmental evaluations (normally nonhydraulic effects) are required for project construction as well as operation. Navigation locks affect the local economy both in the short term, by construction activities, and in the long term, by the presence of navigation traffic. Visual changes are the major aesthetic effects of navigation lock projects.

**7-26. Water Quality**

Concerns experienced at other types of hydraulics structure/s are uncommon. Even valve design, which may cause a small change in water quality during the time the valve is vented and significant air entrainment occurs, has not been a significant environmental concern, because of intermittent lockages. Very few studies of change in water quality due to lock operation (see item R8, for example) are available; these studies in general do not show a meaningful deterioration in water quality and very limited possibilities for enhancement.

**7-27. Recreational Craft**

For projects where recreational craft appear in considerable quantities, the introduction of separate handling facilities is considered particularly when the period of peak recreational demand corresponds to the period of peak commodity movement. Separate facilities (such as a canvas sling or steel tank to lift the craft, a separate small lock, an inclined plane moving lock) are discussed briefly in Appendix G.

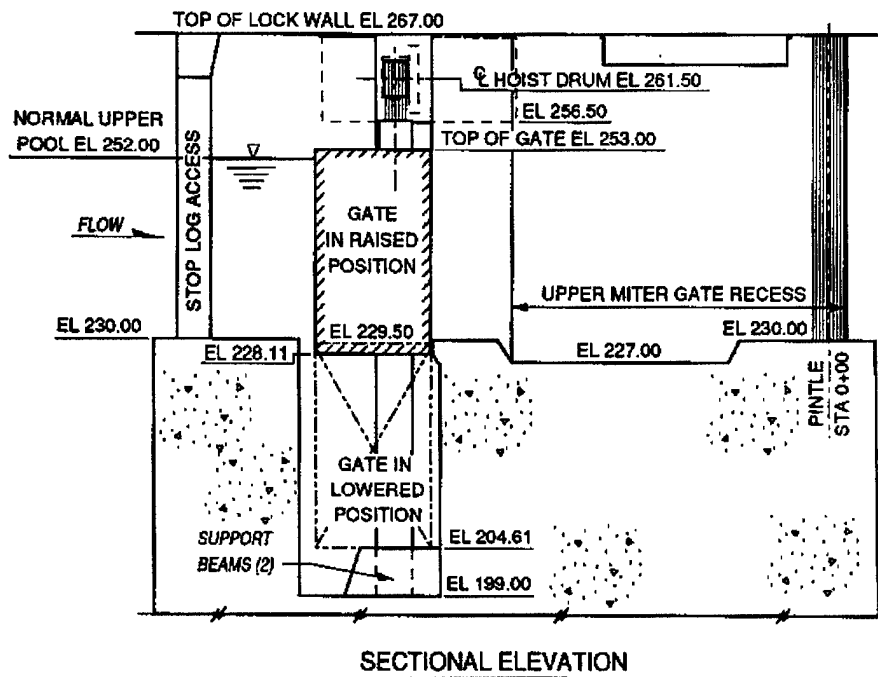
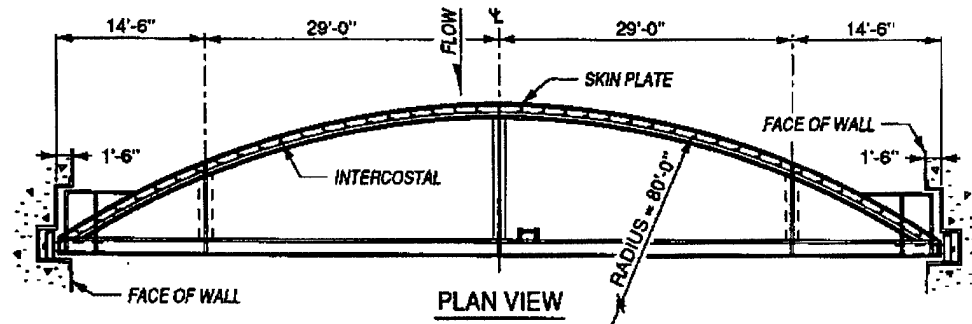
**7-28. Facility Alternatives**

Several alternatives for providing separate facilities for recreational craft for the Upper Mississippi River have been considered. These included the following:

- a. A 110-ft by 360-ft auxiliary chamber.
- b. A 110-ft by 400-ft auxiliary chamber.
- c. A mobile floating lock.
- d. A small-scale steel lock.
- e. A differential railway lift.
- f. A steel tank on inclined rails.
- g. A steel tank lift crane.
- h. A mobile boat carrier.
- i. An inclined channel lift.
- j. An inclined plane lift.

**7-29. Second Lock Chamber**

Twenty of the Upper Mississippi River locks have partial provisions for a second lock chamber, 100 ft by 360 ft. These provisions include an upper gate sill, upper portion of the river wall, and recesses in the intermediate wall for the lower miter gate and gate machinery. Completion of this lock chamber would involve damming and dewatering the chamber area; removing accumulated debris and scour protection measures; constructing the river wall and chamber floor; removing and rehabilitating the upper miter gate; and installing gates, valves, operating machinery, and appurtenances.



EMERGENCY CLOSURE SYSTEM  
PLAN II  
VERTICAL LIFT GATE

Plate 7-1

## Appendix A References

### A-1. HQUSACE Publications

**ER 1110-1-8100**

Laboratory Investigations and Material Testing

**ER 1110-2-8152**

Planning and Design of Temporary Cofferdams and Braced Excavation

**EM 1110-2-1602**

Hydraulic Design of Reservoir Outlet Works

**EM 1110-2-1605**

Hydraulic Design of Navigation Dams

**EM 1110-2-1606**

Hydraulic Design of Surges in Canals

**EM 1110-2-1610**

Hydraulic Design of Lock Culvert Valves

**EM 1110-2-1611**

Layout and Design of Shallow-Draft Waterways

**EM 1110-2-1612**

Ice Engineering

**EM 1110-2-1613**

Hydraulic Design of Deep Draft Navigation Projects

**EM 1110-2-2002**

Evaluation and Repair of Concrete Structures

**EM 1110-2-2602**

Planning and Design of Navigation Lock Walls and Appurtenances

**EM 1110-2-2703**

Lock Gates and Operating Equipment

**ETL 1110-2-532**

Reliability Assessment of Navigation Structures

**Hydraulic Design Criteria (HDC) sheets and charts.**

Available from U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-IM-MI-S, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. A fee of \$10 is charged to non-Government requestors.

**Con conversationally Oriented Real-Time Programming System (CORPS) computer programs.** Available from U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-IM-DS, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

### A-2. CE-Sponsored Lock Hydraulic System Study Reports

Note: The following references are available on inter-library loan from the Research Library, ATTN: CEWES-IM-MI-R, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

The availability of data presented in the following listing of reports is summarized in Appendix C.

<u>Number</u>	<u>Laboratory Code and Report Number</u>		<u>Description</u>
01	STP No. 19	Apr 1937	"Laboratory Tests on Hydraulic Model of Pickwick Lock Hydraulic System, Tennessee River, Pickwick Landing, Tennessee."
02	STP No. 21	Jul 1937	"Laboratory Tests on Hydraulic Model of Guntersville Lock Hydraulic System, Tennessee River, Guntersville, Alabama."
03	STP No. 27	Dec 1937	"Laboratory Tests on Hydraulic Model of Filling and Emptying System for Proposed Watts Bar Project Lock, Tennessee River, near Dayton, Tennessee."
04	STP No. 28	Dec 1937	"Hydraulic Model Tests of the Filling and Emptying System for the Chickamauga Project Lock, Tennessee River."
05	STP No. 34	Jul 1939	"Laboratory Tests on Hydraulic Model of Filling and Emptying System of the General Joe Wheeler Lock, Tennessee River, near Florence, Alabama."
06	STP No. 44	Nov 1940	"Laboratory Tests on Hydraulic Model to Determine Navigation Conditions in Approaches to St. Anthony Falls Locks, Mississippi River, Minneapolis, Minnesota".
07	BHL TR No. 8-1	Jun 1941	"Model Study of the Willamette Falls Locks, Oregon City, Oregon."
08-13	STP No. 46	Oct 1941	"Prototype Lock Hydraulic Tests to Verify Model Experiments." (This volume contains reports on studies of six separate lock systems.)
14	STP No. 48	Feb 1944	"Laboratory Tests on Hydraulic Model of Filling and Emptying System for the MacArthur Lock, St. Marys River, Sault Ste. Marie, Michigan."
15	STP No. 49	Feb 1944	"Laboratory Tests on Hydraulic Models of Filling and Emptying Systems for the New Lock No. 2, Mississippi River, Hastings, Minnesota."
16	STP No. 51	Aug 1945	"Laboratory Test on Hydraulic Models of a Submergible Tainter Lock Gate for St. Anthony Falls Lower Lock, Mississippi River, Minneapolis, Minnesota," by Warner and Hartigan.
17	STP No. 52	Jun 1946	"Laboratory Tests on Models of Lock Hydraulic Systems," by Webster, Warner, Hartigan, and Nelson.
18	WES TM 2-282	Jun 1949	"Vacuum Tank Tests of Model Tainter Valve for McNary Dam."
19	WES TM 2-313	Jun 1950	"Study of Butterfly Valves for Pearl River Locks; Model Investigation."
20	WES TM 2-309	Apr 1951	"Filling Characteristics, Algiers Lock, Intracoastal Waterway, Gulf Section, Louisiana; Model Investigation."

<u>Number</u>	<u>Laboratory Code and Report Number</u>		<u>Description</u>
21	STP No. 56	Aug 1952	"Laboratory Tests on Hydraulic Models of Filling and Emptying Systems for the New Cumberland Locks, Ohio River."
22	WES TM 2-358	Apr 1953	"Upstream Emergency Dam, Cheatham Lock, Cumberland River, Tennessee; Hydraulic Model Investigation."
23	STP No. 59	Jan 1955	"Laboratory Tests on Hydraulic Models of Filling and Emptying Systems for Auxiliary Locks, Mississippi River."
24	BHL TR No. 26-1	May 1955	"Navigation Lock for McNary Dam, Columbia River, Oregon and Washington; Hydraulic Model Investigation."
25	WES MP 2-146	Nov 1955	"Prototype Tests of Filling and Emptying Systems, McNary Dam Lock, Washington, October 1955."
26	STP No. 565	Mar 1957	"Laboratory Tests on Hydraulic Model to Determine Hawser Pull on Short Tows near Cumberland Main Lock, Ohio River, Suppl. Report," by D. L. Preston and J. J. Hartigan.
27	WES TR 2-497	Apr 1959	"Filling and Emptying Characteristics of Calumet-SAG Project, Illinois; Hydraulic Model Investigation," by J. H. Ables.
28	WES TR 2-500	May 1959	"Filling and Emptying System, Port Allen Navigation Lock, Gulf Intracoastal Waterway, Louisiana; Hydraulic Model Investigation," by J. H. Ables.
29	WES TR 2-519	Aug 1959	"Walter F. George Lock and Dam, Chattahoochee River, Alabama and Georgia; Hydraulic Model Investigation," by E. S. Melsheimer.
30	WES TR 2-527	Oct 1959	"Emergency Gate, Greenup Locks, Ohio River, Kentucky; Hydraulic Model Investigation," by E. S. Melsheimer.
31	STP No. 64	Oct 1959	"Laboratory Tests on Hydraulic Models of Filling and Emptying Systems for Chain of Rocks Locks, Mississippi River."
32	STP No. 68	Mar 1960	"Laboratory Tests on Hydraulic Models of the Filling and Emptying Systems for Jackson Lock, Tombigbee River, Alabama."
33	STP No. 69	May 1960	"Lower Lock and Dam Tainter Gates, St. Anthony Falls Upper Harbor Project, Mississippi River, Minneapolis, Minnesota; Hydraulic Model Investigation."
34	WES TR 2-549	Jun 1960	"Filling and Emptying System, Old River Navigation Lock, Louisiana; Hydraulic Model Investigation," by J. H. Ables and F. R. Brown.
35	WES TR 2-552	Jun 1960	"Hydraulic Prototype Tests of Tainter Valve, McNary Lock, Columbia River, Washington," by E. B. Pickett.

<u>Number</u>	<u>Laboratory Code and Report Number</u>		<u>Description</u>
36	WES TR 2-556	Aug 1960	"Filling and Emptying Characteristics of Barge Canal Lock, Sacramento River Deep-Water Ship Channel Project, California; Hydraulic Model Investigation," by J. H. Ables and T. E. Murphy.
37	WES TR 2-561	Apr 1961	"Filling and Emptying System, New Poe Lock, St. Marys River, Sault Ste. Marie, Michigan; Hydraulic Model Investigation," by J. H. Ables and T. Schmidtgal.
38	STP No. 70	Apr 1961	"Intake Manifolds for Demopolis and Warrior Locks, Tombigbee River, Alabama, and Jim Woodruff Lock, Apalachicola River, Florida; Hydraulic Model Investigation," by F. T. Mertes and M. E. Nelson.
39	WES TR 2-537	Jun 1961	"Culvert Tainter Valves, New Lock No. 19, Mississippi River; Hydraulic Model Investigation."
40	STP No. 71	Jun 1961	"Filling and Emptying Systems for Dwight D. Eisenhower and Bertrand H. Snell Locks, St. Lawrence Seaway Project; Hydraulic Model Investigation," by S. Fidelman.
41	WES TR 2-573	Jul 1961	"Intake Studies, Dardanelle Lock, Arkansas River, Arkansas; Hydraulic Model Investigation," by J. H. Ables.
42	STP No. 73	Sep 1961	"Filling and Emptying Systems for Walter F. George Lock, Chattahoochee River, Alabama-Georgia; Hydraulic Model Investigation," by S. Fidelman and M. E. Nelson.
43	STP No. 74	Jan 1962	"Filling and Emptying Systems for Greenup and Markland Locks, Ohio River; Hydraulic Model Investigation," by J. J. Hartigan and F. J. Ryder.
44	STP No. 65	Jun 1962	"Laboratory Tests on Hydraulic Models of Filling and Emptying Systems for a Proposed 600-ft Lock and Dam No. 19, Mississippi River, Keokuk, Iowa; Hydraulic Model Investigation."
45	BHL TR No. 111-1		"Miter Gate Bottom Seals, Panama Canal Locks; Laboratory Investigation."
46	STP No. 66	Jun 1963	"Filling and Emptying Systems for New 1200-ft Lock No. 19, Mississippi River, Keokuk, Iowa; Hydraulic Model Investigation," by D. L. Preston and J. J. Hartigan.
47	STP No. 75	Jun 1963	"Filling and Emptying Systems for Barkley Lock, Cumberland River, Kentucky; Hydraulic Model Investigation," by S. Fidelman.
48	WES MP 2-622	Feb 1964	"Emergency Gate Performance, McAlpine Lock, Ohio River, Kentucky; Hydraulic Prototype Tests."
49	WES TR 2-651	Jun 1964	"Operating Forces on Miter-Type Lock Gates," by J. L. Grace, T. E. Murphy, and F. R. Brown.



<u>Number</u>	<u>Laboratory Code and Report Number</u>		<u>Description</u>
50	STP No. 76	Dec 1964	"Filling and Emptying Systems for St. Anthony Falls Locks, Mississippi River, Minnesota; Hydraulic Model Investigation," by S. Fidelman and J. J. Hartigan.
51	WES TR 2-678	Jun 1965	"Filling and Emptying System, Jonesville Lock, Ouachita-Black Rivers, Louisiana; Hydraulic Model Investigation," by N. R. Oswalt, J. H. Ables, M. B. Boyd, and T. E. Murphy.
52	BHL TR No. 56-1	May 1965	"Navigation Lock, The Dalles Dam, Columbia River, Oregon and Washington; Hydraulic Model Investigation," by M. J. Webster and H. P. Theus.
53	WES TR 2-685	Aug 1965	"Prototype Hawser-Force Measurements, Jackson Lock, Tombigbee River, Alabama," by J. V. Dawsey, C. J. Huval, and W. C. Blanton.
54	WES TR 2-689	Aug 1965	"Tests of Structure Orientation, Spillway, and Lock Emergency Gate, Barkley Lock and Dam, Cumberland River, Kentucky; Hydraulic Model Investigation," by T. E. Murphy and R. S. Cummins.
55	WES TR 2-698	Nov 1965	"Lock Filling and Emptying System, Holt Lock and Dam, Warrior River, Alabama; Hydraulic Model Investigation," by T. E. Murphy and J. H. Ables.
56	WES MP 2-794	Feb 1966	"Lock Culvert Outlet Basins; Hydraulic Model Investigation," by J. H. Ables and M. B. Boyd.
57	WES TR 2-713	Feb 1966	"Filling and Emptying System, Cannelton Main Lock, Ohio River, and Generalized Tests of Sidewall Port Systems for 110- by 1200-ft Locks; Hydraulic Model Investigation," by J. H. Ables and M. B. Boyd.
58	WES TR 2-718	Mar 1966	"Filling and Emptying Systems, Millers Ferry and Jones Bluff Locks, Alabama River, Alabama; Hydraulic Model Investigation," by J. H. Ables and M. B. Boyd.
59	WES TR 2-734	Jul 1966	"Culvert Pressures, Greenup Lock, Ohio River, Kentucky; Hydraulic Prototype Tests," by P. M. Smith and R. A. Yates.
60	WES TR 2-739	Sep 1966	"Filling and Emptying System, Cordell Hull Navigation Lock, Cumberland River, Tennessee; Hydraulic Model Investigation," by N. R. Oswalt and M. B. Boyd.
61	WES TR 2-743	Nov 1966	"Filling and Emptying Systems, Low-Lift Locks, Arkansas River Project; Hydraulic Model Investigation," by J. H. Ables and M. B. Boyd.
62	WES TR 2-778	May 1967	"Modernization of Filling and Emptying System, Existing McAlpine Lock (Old No.41), Ohio River, Louisville, Kentucky; Hydraulic Model Investigation," by J. H. Ables and T. E. Murphy.

<u>Number</u>	<u>Laboratory Code and Report Number</u>		<u>Description</u>
63	WES TR H-68-4	Sep 1968	"Effect of Valve Position in a Sidewall Port Filling System, Newburgh Lock, Ohio River; Hydraulic Model Investigation," by J. O. Farrell and J. H. Ables.
64	WES TR H-69-5	Apr 1969	"Filling and Emptying System, Dardanelle Lock, Arkansas River; Hydraulic Model Investigation," by J. H. Ables and M. B. Boyd.
65	WES TR H-70-2	Mar 1970	"Operating Forces on Sector Gates Under Reverse Heads; Hydraulic Model Investigation," by N. R. Oswalt.
		Dec 1979	"Appendix A: Results of Supplemental Tests; Hydraulic Model Investigation," by N. R. Oswalt and T. E. Murphy.
66	WES MP H-71-4	Feb 1971	"Calcasieu Saltwater Barrier Prototype Sector Gate Tests," by D. F. Bastian.
67	WES TR H-72-6	Sep 1972	"Navigation Conditions and Filling and Emptying System, New Bankhead Lock, Black Warrior River, Alabama; Hydraulic Model Investigation," by N. R. Oswalt, J. H. Ables, and T. E. Murphy.
68	BHL TR No. 32-1	May 1973	"Filling and Emptying System, Ice Harbor Lock, Snake River, Washington; Hydraulic Model Investigation," by L. Z. Perkins.
69	BHL TR No. 98-1	Jul 1974	"Filling and Emptying System, John Day Lock, Columbia River, Oregon and Washington; Hydraulic Model Investigation," by A. J. Chanda and L. Z. Perkins.
70	BHL TR No. 105-1	May 1975	"Intake Manifolds and Emptying Valves for Lower Monumental Lock, Snake River, Washington," by A. J. Chanda and L. Z. Perkins.
71	WES TR H-75-11	Jun 1975	"Barkley Lock Prototype Tests, Cumberland River, Kentucky," by F. M. Neilson.
72	WES MP H-75-7	Jul 1975	"Lock Design, Sidewall Port Filling and Emptying System," by T. E. Murphy.
73	BHL TR No. 115-1	Sep 1975	"Filling and Emptying System, Little Goose Lock, Snake River, Washington; Hydraulic Model Investigation," by A. J. Chanda and L. Z. Perkins.
74	WES TR H-77-7	Apr 1977	"Filling and Emptying System for Medium-Lift Locks, Trinity River, Texas; Hydraulic Model Investigation," by N. R. Oswalt.
75	WES TR H-78-9	Jun 1978	"Bay Springs Canal Surge Study, Tennessee-Tombigbee Waterway, Mississippi and Alabama; Hydraulic Model Investigation," by C. H. Tate, Jr.
76	WES MP H-78-10	Sep 1978	"Single-Valve Prototype Tests, Main Lock, Locks and Dam 26, Mississippi River, Alton, Illinois," by E. D. Hart.

<u>Number</u>	<u>Laboratory Code and Report Number</u>		<u>Description</u>
77	WES TR H-78-16	Sep 1978	"Filling and Emptying System, New Ship Lock, Mississippi River-Gulf Outlet, Louisiana; Hydraulic Model Investigation," by J. H. Ables, Jr.
78	WES TR H-78-19	Nov 1978	"Filling and Emptying System for Bay Springs Lock, Tennessee-Tombigbee Waterway, Mississippi; Hydraulic Model Investigation," by J. H. Ables, Jr.
79	BHL TR No. 126-1	Sep 1979	"Navigation Lock for Lower Granite Dam, Snake River, Washington; Hydraulic Model Investigations," by L. Z. Perkins.
80	WES TR HL-79-21	Dec 1979	"Modifications to Filling and Emptying System of Lock No. 1, Mississippi River, Minneapolis, Minnesota; Hydraulic Model Investigation," by J. H. Ables, Jr.
81	WES TR HL-80-13	Aug 1980	"Prototype Filling and Emptying System Measurements, New Bankhead Lock, Black Warrior River, Alabama," by A. R. Tool (includes Appendixes A-B).
82	WES TR HL-80-17	Sep 1980	"Lock Approach Canal Surge and Tow Squat at Lock and Dam 17, Arkansas River Project; Mathematical Model Investigation," by C. J. Huval (includes Appendix A).
83	WES TR HL-81-10	Sep 1981	"Lock Culvert Valve Loss Coefficients; Hydraulic Model Investigation," by G. A. Pickering.
84	BHL TR No. 194-1	Apr 1983	"Emergency Closure System and Flood Control Regulation Gate for Hiram M. Chittenden Locks at Lake Washington Ship Canal; Hydraulic Model Investigation," by M. M. Kubo.
85	WES TR HL-84-8	Sep 1984	"Filling and Emptying System, Walter Bouldin Lock, and Lock Culvert Valve for Coosa River Waterway, Alabama; Hydraulic Model Investigation," by J. F. George.
86	WES Draft		"John Day Lock Hydraulic Prototype Tests, Columbia River, Washington," by E. B. Pickett and F. M. Neilson.

30 Jun 95

## A-3. General Bibliography

The following bibliographic items contain material pertinent to various aspects of hydraulic design of locks. The CE-sponsored reports, pertinent to filling and emptying systems and included in paragraph A-2, are excluded.

Number	Description	Number	Description
A1	American Society of Civil Engineers, "Hydraulic Models," <i>Manual of Engineering Practice No. 25</i> , Committee of the Hydraulics Division on Hydraulics Research, 1942.	B2	McPherson, M. B., Apr 1960; Kohler, W. H., Apr 1960; Robertson, J. M., and Bennett, H. W., May 1960; Tinney, E. R., May 1960; Advani, C. I., Jun 1960; Ball, J. W., Jan 1961.)
A2	American Society of Civil Engineers, "Manual on Lock Valves," <i>Manual of Engineering Practice No. 3</i> , Committee of the Waterways Division on Lock Valves, 1930.	B3	Ball, J. W., "Cavitation Design Criteria, Control of Flow in Closed Conduits," <i>Proceedings of the Institute</i> held at Colorado State University, Ft. Collins, Colo., 9-14 Aug 1970.
A3	American Society of Civil Engineers, "Nomenclature for Hydraulics," <i>Manuals and Reports on Engineering Practice No. 43</i> , Task Force of the Hydraulics Division on Nomenclature for Hydraulics, 1962.	B4	Blanchett, Ch., and Quetin, B., "Mardyck Lock Acts as Salt-Water Barrier," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 98, No. WW4, Proc. Paper 9387, Nov 1972.
A4	American Society of Mechanical Engineers, "American Standard Letter Symbols for Hydraulics," ASA Y10-1958, 1958.	B5	Blee, C. E., "Structural Elements for Emergency Closures and Unwatering Operations," <i>Transactions, ASCE</i> , Vol 116, 1951, pp 853-863.
A5	Armstrong, R. C., "Replacement-Lock and Dam No. 26: Plans Considered," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 96, No. WW1, Proc. Paper 7071, Feb 1970.	B6	Bloor, R. W., "Lock Sizes for Inland Waterways," <i>Transactions, ASCE</i> , Vol 116, 1951, pp 864-888.
A6	Ayers, J. R., Burnett, A. L., and Stokes, R. C., "The Dry Dock Lock," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 89, No. WW2, Proc. Paper, May 1963. (Discussion: Jelley, J. F., Jr., Nov 1964; Bath, P. M., Nov 1964; Ayers, J. R., et al., May 1965.)	B7	Bottoms, E. E., "Practical Tonnage Capacity of Canalized Waterways," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 92, No. WW1, Proc. Paper 4644, Feb 1966. (Discussion: Santana, Wm. J. and Wesler, G. B., Aug 1966; Wellons, C. M., Aug 1966, Mahaffey, B. R., and Ferguson, W. I., Nov 1966; Lang, E. H., Nov 1966; Hallock, H. R., Nov 1966; Zeller, E. E., Nov 1966; Eden, E. W., Jr., Nov 1966; Mullaney, H. J., Nov 1966; Gaum, C. H., Nov 1966; Bottoms, E. E., May 1967.)
B1	Ball, J. W., "Hydraulic Characteristics of Gate Slots," <i>Journal of the Hydraulics Division, ASCE</i> , Vol 85, No. HY10, Proc. Paper 2224, Oct 1959. (Discussion: Thiruvengadam, A., Apr 1960;	B8	Broome, K. R., and Gaither, W. S., "Floating Dry Docks For Ship Launching," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 96, No. WW1, Proc. Paper 7110, Feb 1970.

Number	Description	Number	Description
B9	Brown, F. R., "Model Studies of Sector Gate Type Locks," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW4, Proc. Paper 1767, Sep 1958.		<i>Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW2, Proc. Paper 938, Apr 1956.
B10	Brown, F. R., "Cavitation in Hydraulic Structures: Problems Created by Cavitation Phenomena," <i>Journal of the Hydraulics Division, ASCE</i> , Vol 89, No. HY1, Proc. Paper 3393, Jan 1963. (Discussion: Misra, M. S., Sep 1963; Campbell, F. B., Sep 1963; Brown, F. R., Mar 1964.)	C5	Cleary, W. E., "Bridge Clearance: Problem Needs Realistic Approach," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW2, Proc. Paper 937, Apr 1956. (Note Appendix A: Statement of Policy, Practice, and Procedures on Bridges, Office of the Chief of Engineers, 3 Nov 1954.)
B11	Brown, F. R., "Navigation Locks: End Filling and Emptying Systems," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 90, No. WW1, Proc. Paper 3782, Feb 1964. (Discussion: Schijf, J. B., Nov 1964; Brown, F. R., Aug 1965.)	C6	Corey, J. B. W., "Calumet-Sag Navigation Project," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW3, Proc. Paper 1643, May 1958.
B12	Burpee, L. H., "Canadian Section of the St. Lawrence Seaway," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 86, No. WW1, Proc. Paper 2420, Mar 1960.	C7	Cummings, E. M., "Cellular Cofferdams and Docks," ASCE Separate, Proc. Paper 1366, Sep 1957. (Discussions: Heyman, S., Mar 1958; Erzen, C. Z., Mar 1958; Cummings, E. M., Sep 1958.)
C1	Campbell, F. B., and Pickett, E. B., "Prototype-Performance and Model-Prototype Relationship," Section 3 of <i>Handbook of Applied Description Hydraulics</i> , (ed. by Davis, C. V., and Sorenson, K. E.) McGraw-Hill Book Company, New York, 1969.	D1	Daggett, L. L., and Ankey, T. D., "Determination of Lock Capacities Using Simulation Modeling," MP H-75-9, US Army Engineer Waterways Experiment Station, Vicksburg, Miss., Dec 1975.
C2	Carr, B. B., "Barge Transportation-Energizer of Production and Marketing," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 95, No. WW2, Proc. Paper 6559, May 1969.	D2	Daggett, L. L., "Sensitivity of Base Data in the Analysis of Lock Capacity: A Case Study of Lock and Dam 26, Mississippi River," TR HL-79-11, US Army Engineer Waterways Experiment Station, Vicksburg, Miss., Jul 1979.
C3	Carter, W. A., and Brown, R. D., Jr., "Overhaul of Locks in the Canal Zone," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 88, No. WW1, Proc. Paper 3047, Feb 1962.	D3	Davis, J. P., "The American Locks of the St. Lawrence Seaway," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW4, Proc. Paper 1771, Sep 1958.
C4	Caruthers, N. L., "Bridge Clearances: The Operator's View," <i>Journal of the</i>	D4	Davis, J. P., "Tonnage Capacity of Locks," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 95, No. WW2, Proc. Paper 6577, May 1969. (Discussion: Chandler, A. R., Nov 1969; Bottoms, E. E., Feb 1970; Davis, J. P., Aug 1970.)

30 Jun 95

<u>Number</u>	<u>Description</u>	<u>Number</u>	<u>Description</u>
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D6	Davis, J. P., and Murphy, T. E., "Experimental Research on Lock Hydraulic Systems," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 92, No. WW1, Proc. Paper 4643, Feb 1966.	D13	Dyer, H. B., "Modern Towboat and Barge Design," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW5, Proc. Paper 1122, Dec 1956.
D7	Decker, E. R., "Replacement-Lock and Dam No. 26: History, Objectives, and Scope," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 96, No. WW1, Proc. Paper 7070, Feb 1970.	D14	Dykes, A. E., "Lower Cumberland Project: Kentucky and Tennessee," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW4, Proc. Paper 1062, Sep 1956.
D8	de Neufville, R., and Hoffmeister, J. F., II, "Optimizing the Supply of Inland Water Transportation," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 99, No. WW3, Proc. Paper 9926, Aug 1973.	E1	Edwards, F. W., and Soucek, E., "Surges in Panama Canal Reproduced in Model," <i>Transactions, ASCE</i> , Vol 110, 1945. (Discussion: Weggel, H. A.; Leypoldt, H.; Posey, C. J.; Edwards, F. W., and Soucek, E.)
D9	DeSalvo, J. S., "On Acceleration of Barge Tows," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 95, No. WW2, Proc. Paper 6545, May 1969. (Discussion: McNow, J. S., May 1970; DeSalvo, J. S., May 1970.)	E2	Eickhorst, A. G., and Koch, D. A., "Replacement-Lock and Dam No. 26: Lock Capacity Procedure and Scope," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 96, No. WW1, Proc. Paper 7094, Feb 1970.
D10	Dittbrenner, E. E., "Bridge Clearances: Problems in Northeastern United States," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW2, Proc. Paper 939, Apr 1956.	E3	Elder, R. A., "'Tidal' Navigation Problems at Wilson Dam," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 85, No. WW1, Proc. Paper 1983, Mar 1959.
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D12	Dorland, G. M., and Bethurum, G. R., Jr., "Growth of Commerce: Tennessee	E5	Elms, D. G., and Schmid, W. E., "Structural Action of Pile Cluster Dolphins," <i>Journal of the Waterways and Harbors Description Division, ASCE</i> , Vol 91, WW4, Proc. Paper 4529, Nov 1965.

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F1	Falvey, H. T., "Air-Water Flows in Hydraulic Structures," Engineering Monograph No. 41, U.S. Department of the Interior, Water and Power Resources Service (USBR), Denver, Colo., Dec 1980.	H1	Harich, H. W., "Reducing Ice Formation at Navigation Dams," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 98, No. WW3, Proc. Paper 9114, Aug 1972.
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F3	Fortson, E. P., and Fenwick, G. B., "Navigation Model Studies of New Ohio River Locks," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 86, No. WW2, Proc. Paper, Jun 1960.	H3	Hochstein, H. A., "Optimum Dredged Depth in Inland Waterway," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 101, No. WW4, Proc. Paper 11698, Nov 1975.
F4	Franco, J. J., "Development of Alluvial Streams for Navigation," MP H-71-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Jan 1971.	H4	Holmes, R. E., "Navigation on the Columbia River," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW4, Proc. Paper 1789, Sep 1958. (Discussion: Hickson, P. E., Mar 1959; Holmes, R. E., Sep 1959.)
G1	Grum, C. H., "History and Future of Ohio River Navigation," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 96, No. WW2, Proc. Paper 7304, May 1970. (Discussion: Gleser, S. M., Feb 1971; Gaum, C. H., Nov 1971.)	H5	Horstman, W. L., "Barge Docks for Inland Waterways," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 90, No. WW4, Proc. Paper 4146, Nov 1964.
G2	Griffin, A. F., "Influence of Model Testing on Lock Design," <i>Transactions, ASCE</i> , Vol 116, 1951, pp 831-852. (Discussion: Standing, B., page 889; Griffin, A. F., pp. 889-890.)	H6	Horton, R., Jr., "Scientific Developments in River Transportation," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW4, Proc. Paper 1772, Sep 1958. (Discussion: Li, S. T., Mar 1959.)
G3	Grzywienski, A. M., "A Navigation Lock That Is Also a Spillway," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 93, No. WW3, Proc. Paper 5401, Aug 1967.	H7	Howe, C. W., "Mathematical Model of Barge Tow Performance," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 93, No. WW4, Proc. Paper 5588, Nov 1967.
G4	Gullidge, E. J., and Urabeck, F. J., "Planning for Pleasure Boating on a Regional	H8	Hudowalski, E. C., "New York State Barge Control System," <i>Journal of the Waterways and Harbors Division, ASCE</i> ,

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J1	Jaeger, C., <i>Engineering Fluid Mechanics</i> , translated by P. O. Wolf, St. Martin's Press, Inc., New York, 1957.	M1	Marshall, D. P., Jr., "Replacement-Lock and Dam No. 26: Condition of Existing Structure," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 96, No. WW1, Proc. Paper 7097, Feb 1970. (Discussion: Marshall, D. P., Jr.)
K1	Koch, D. A., "Replacement-Lock and Dam No. 26: Projecting Waterborne Commerce-Inland Navigation," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 96, No. WW1, Proc. Paper 7100, Feb 1970.	M2	Martin, L. D., "Locks and Dam 52 - Prototype Tests of Temporary Lock," unpublished memorandum, U.S. Army Engineer District, Louisville, Louisville, Ky., Jun 1985.
K2	Koch, D. A., "Implication of System Analysis to Inland Navigation," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 97, No. WW3, Proc. Paper 8302, Aug 1971.	M3	McDonald, W. E., "Deep-Draft Navigation on the Great Lakes," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 85, No. WW4, Proc. Paper 2298, Dec 1959.
K3	Kooman, C., "Navigation Locks for Push Tows, Rijkswaterstaat," Communications No. 16, Government Publishing Office, The Hague, The Netherlands, 1973.	M4	McIntyre, D., "The Beauharnois Canal Locks," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW4, Proc. Paper 1781, Sep 1958.
K4	Krauss, F. E., and Plude, G. H., "1200-Ft Graving Dock," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 98, No. WW4, Proc. Paper 9389, Nov 1972.	M5	McNown, J. S., "Surges and Water Hammer, Engineering Hydraulics," <i>Proceedings of the Fourth Hydraulics Conference</i> , Iowa Institute of Hydraulic Research, June 12-15, 1949, H. Rouse (ed.), John Wiley and Sons, Inc., New York, 1950.
K5	Kurylo, W., "Bridge Clearances: The Interest of the Bureau of Public Roads," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW2, Proc. Paper 936, Apr 1956.	M6	McNown, J. S., "Mechanics of Manifold Flow," <i>Transactions, ASCE</i> , Vol 119, 1954. (Discussion: Escobar, J.; Carstens, M. K., and Roberson, J.; Hartigan, J. J.; Niaz, S. M.; Barton, J. R.; Powell, R. W.; Vennard, J. K., and Denton, D. I.; McNown, J.)
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M7	McNown, J. S., "Fluid Mechanics and Lock Design," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 93, No. WW3, Proc. Paper 5365, Aug 1967. (Discussion: Gray, M. H., III, May 1968.)		Nov 1964; Nelson, M. E., and Johnson, H. J., May 1965.)
M8	McNown, J. S., "Sinkage and Resistance for Ships in Channel," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 102, No. WW3, Proc. Paper 12291, Aug 1976. (Discussion: van de Kaa, E., Aug 1977; McNown, J. S., May 1978.)	O1	O'Brien, J. T., and Kuchenreuther, D. I., "Forces Induced on a Large Ship by Surge," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW2, Proc. Paper 1571, Mar 1958. (Discussion: Wilson, B. W., Dec 1958; Wilson, B. W., Mar 1959; O'Brien, J. T., and Kuchenreuther, D. I., Jun 1959.)
M9	Michiels, C. F., Lail, W. F., and Mytinger, R. E., "Current Trends in Ohio River Traffic and Equipment," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW5, Proc. Paper 1123, Dec 1956.	O2	O'Neil, W. A., "The Welland Canal," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW2, Proc. Paper 1570, Mar 1958.
M10	Miller, D. S., "Internal Flow Systems," British Hydromechanics Research Association, BHRA Fluid Engineering, Cranfield, Bedford MK43 OAJ, England, 1978.	O3	Oswalt, N. R., "Ice Flushing from St. Lawrence Seaway Locks; Hydraulic Model Investigation," TR H-76-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Jul 1976.
M11	Moore, N. R., "New Locks on the Lower Mississippi and Gulf Coast," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW3, Proc. Paper 969, May 1950.	P1	Parfenscky, H. W., "Waves in Navigation Canals Due to Lock Filling," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 86, No. WW1, Proc. Paper 2422, Mar 1960. (Discussion: Escoffier, F. F., Sep 1960; Thijssse, J. Th., Nov 1960; Baines, W. D., and Leutheusser, H. J., Nov 1960.)
M12	Murphy, T. E., "Lock Design, Bottom Longitudinal Filling and Emptying System," MP HL-80-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Sep 1980.	P2	Pariset, E., and Gagnon, A., "High Lift Locks: Some Hydraulic Problems and Solutions," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 90, No. WW4, Proc. Paper 4131, Nov 1964. (Discussion: Wisner, P., and Stoicescu, T., Aug 1965; Pariset, E., and Gagnon, A., Feb 1966.)
N1	Nelson, A., and Nelson, K. D., <i>Dictionary of Water and Water Engineering</i> , CRC Press, Cleveland, Ohio, 1973.	P3	Passage, J. T., and Plump, J. H., Jr., "River Lock Rehab: A Winter's Tale," <i>Civil Engineering</i> , Vol 94, No. 5, ASCE, New York, May 1984.
N2	Nelson, M. E., and Johnson, H. J., "Navigation Locks: Filling and Emptying Systems for Locks," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 90, No. WW1, Proc. Paper 3789, Feb 1964. (Discussion: Kabelac, O. W.,	P4	Pickering, G. A., "Filling and Emptying Systems for High-Lift Navigation Locks,"

30 Jun 95

Number	Description	Number	Description
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P5	Pickett, E. B., and Neilson, F. M., "Lock Hydraulic System Model and Prototype Study Data; Corps of Engineers Projects 1937-1984," Miscellaneous Paper HL-88-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.	R6	Roberts, P. W., and Blancata, V., "New Retractable Marine Fender System," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW1, Proc. Paper 1513, Jan 1958.
P6	Pillsbury, G. B., "Excess Head in the Operation of Large Locks Through the Momentum of the Water in the Culverts," <i>Professional Memoirs</i> , U.S. Army Corps of Engineers, Vol 7, No. 31, 1915.	R7	Rouse, H., <i>Elementary Mechanics of Fluids</i> , John Wiley and Sons, Inc., New York, 1964.
R1	Rich, G. R., "Navigation Locks," Section 32, <i>Handbook of Applied Hydraulics</i> (ed. by Davis, C. V., and Sorenson, K. E.), McGraw-Hill, New York, 1969.	R8	Russo, E. P., "Flow of Pollutants Through a Lock," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 102, No. WW2, Technical Note, May 1976.
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R3	Richardson, G. C., "Filling System for Lower Granite Lock," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 95, No. WW3, Proc. Paper 6718, Aug 1969.	S2	Santina, W. J., and Wesler, G. B., "Duplicate Locks for Illinois Waterway," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 90, No. WW4, Proc. Paper 4118, Nov 1964. (Discussion: Gullat, D., Aug 1965; Santina, W. J., and Wesler, G. B., Feb 1966.)
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R5	Rigler, H. M., and Chun, E. H., "Vertical Lift Gate Design for the Ice Harbor Lock," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW5, Proc. Paper 1873, Dec 1958.	S4	Schofield, R. R., "Speed of Ships in Restricted Navigation Channels," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 100, 1975; Schofield, R. B., Nov 1975.)
		S5	Schultz, R. P., "Graphic Analysis of Waterway Capacity," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 93, No. WW4, Proc. Paper 5602, Nov 1967. (Discussion: Lang, E. H., Aug 1968; Shultz, R. P., Feb 1969.)

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S6	Soucek, E., and Zelnick, E. W., "Lock Manifold Experiments," <i>Transactions, ASCE</i> , Vol 110, 1945. (Discussion: Pietrkowski, J.; McNown, J. S.; Edwards, F. W.; Lansford, W. M.; Kreiss, R. F.; Berk, R. G.; Powell, R. W.; Soucek, E., and Zelnick, E. W.)	U3	U.S. Department of the Interior, "Hydraulic Laboratory Techniques," Water and Power Resources Service (USBR), Denver, Colo., 1980.
S7	Stepanich, F. C., "Sector Gates in Bangkok Klong System," <i>Journal of Waterways, Harbors, and Coastal Engineering, ASCE</i> , Vol 97, No. WW4, Proc. Paper 8549, Nov 1971.	U4	U.S. Department of the Interior, "Water Measurement Manual," Bureau of Reclamation (USBR), Denver, Colo., 1967.
S8	Stratton, J. H., Douma, J. H., and Davis, J. P., "Navigation Systems," Section 31, <i>Handbook of Applied Hydraulics</i> (ed. by Davis, C. V., and Sorenson, K. E.) McGraw-Hill, New York, 1969.	W1	Weber, E. W., "Bridge Clearances: Policy and Practice," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 82, No. WW2, Proc. Paper 935, Apr 1956.
S9	Svoboda, G. W., "Railroad Bridge Alterations, Calumet-Sag Project," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 84, No. WW3, Proc. Paper 1641, May 1958.	W2	Wilhelms, S. C., "Reaeration at Navigation Locks," US Army Corps of Engineers Information Bulletin, Vol 0-82-5, U.S. Army Engineer Waterways Experiment, Vicksburg, Miss., Dec 1982.
S10	Swatek, E. P., Jr., "Cellular Cofferdam Design and Practice," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 93, No. WW3, Proc. Paper 5398, Aug 1967. (Discussion: Carle, R. J., May 1968; Grayman, R., May 1968.)	W3	Wilson, B. W., "Elastic Characteristics of Moorings," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 93, No. WW4, Proc. Paper 5565, Nov 1967. (Discussion: Joosting, W. C. Q., Aug 1968; Paul, W., Aug 1968; Wilson, B. W., Feb 1969.)
T1	Target W. E., and Funston, R., "Innovation in Barge Transportation on Columbia River," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 96, No. WW2, Proc. Paper 7290, May 1970.	W4	Windsor, J. S., "Hydraulic Assistance on the Welland Ship Canal," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 94, No. WW1, Proc. Paper 5770, Feb 1968. (Discussion: Saarits, R., Nov 1968; Windsor, J. S., May 1969.)
U1	U.S. Army Corps of Engineers, "Engineering Construction, Canalization, Volumes I and II," X-155, The Engineer School, Fort Belvoir, Va., 1940.	W5	Windsor, J. S., and Vallee, H., "Computer Model for a Lock Manifold System," <i>Journal of the Waterways and Harbors Division, ASCE</i> , Vol 95, No. WW2, Proc. Paper 6553, May 1969. (Discussion: Wiggert, D. C., Feb 1970; Windsor, J. S., and Vallee, H., Aug 1970.)
U2	U.S. Army Corps of Engineers, "National Waterways Study: Draft Final Report, A Framework for Decision Making," Institute for Water Resources (IWR), Water Resources Support Center, Ft. Belvoir, Va., 1982.	Y1	Yalin, M. S., <i>Theory of Hydraulic Models</i> , Macmillan Civil Engineering Hydraulics, Macmillan Press Ltd, London, 1971.
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## Appendix B Inventory of Existing Locks

### Section I General

#### B-1. Contents

Existing locks operated by the Corps of Engineers are a broad spectrum of hydraulic design practice. The variation is due to historical development with regard to valves, gates, and manifolds; to increasing demands with regard to higher lifts, shorter operation times, and better chamber performance; and to a similarly broad variation in site-specific constraints. This discussion is a brief overview of materials available in greater detail in the CEWRC-NDC Waterling Bulletin Board System: Navigation and Dredging Data and Reports, Lock Characteristics Data, Physical Characteristics Report. Call CECWR-NDC (703) 355-8562 for details.

Geometric details are also available for a more limited set of designs in the CE computer database CORPS H5300, "CE Lock Hydraulic Model Tests," as described in Chapter 5, main text, and Appendix C.

### Section II Valves and Gates

#### B-2. Valves

Valves control flow into and out of the lock chamber. Several different types have been used, but in recent years all locks with culvert systems have used reverse tainter valves. Recent end systems have used chamber sector gates. The side port flume system (Plate 3-2) uses slide valves. The following six types of valves are in use at existing projects:

- a. Slide valve.
- b. Wagon valve (wheeled vertical-lift valve).
- c. Stoney valve.
- d. Butterfly valve.
- e. Tainter valve.
- f. Reverse tainter valve.

A reverse tainter valve is shown in Figure B-1. Hydraulic design of lock valves is presented in EM 1110-2-1610.

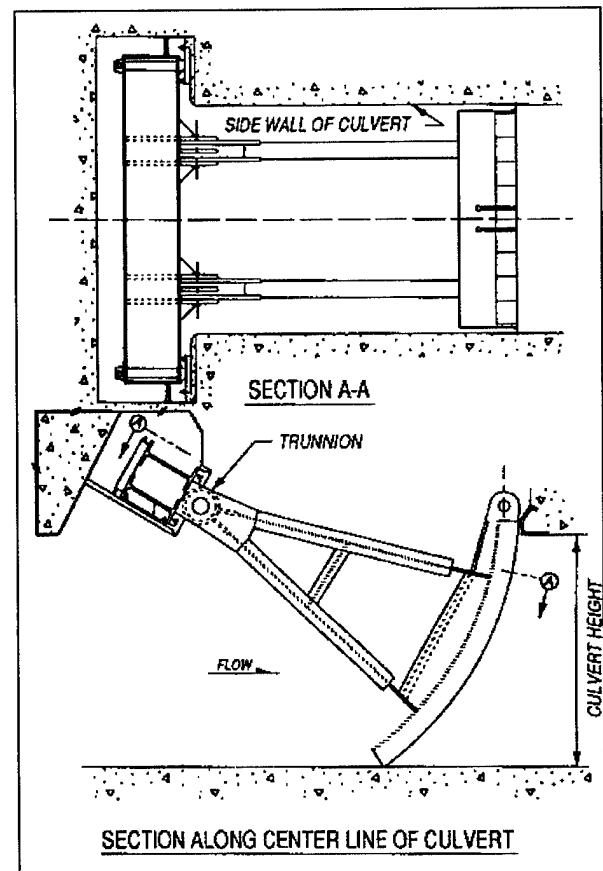


Figure B-1. Reverse tainter valve

#### B-3. Gates

Lock gates provide closure between the chamber and the upper and lower approaches during lock operation and opening for navigation passage at upper and lower pool elevations. Eight types of closure devices are being used for lock gates. Recent end-system design practice is to use vertical-axis sector gates. Other types of designs use (not exclusively) miter gates. The eight existing gate types are described briefly in *a-h* below.

*a. Miter gates.* A miter gate has two parts or leaves. The miter gate derives its name from the fact that the two leaves meet at an angle pointing upstream to resemble a miter joint. Horizontally framed miter gates possess many advantages over other types and have been used on more locks than any other kind. Miter gates are rugged, do not involve complicated construction problems, are easily serviced, and are fast operating. Drawbacks are their inability to operate under head and to withstand substantial reverse head. Figure B-2 illustrates a typical miter gate installation.

30 Jun 95

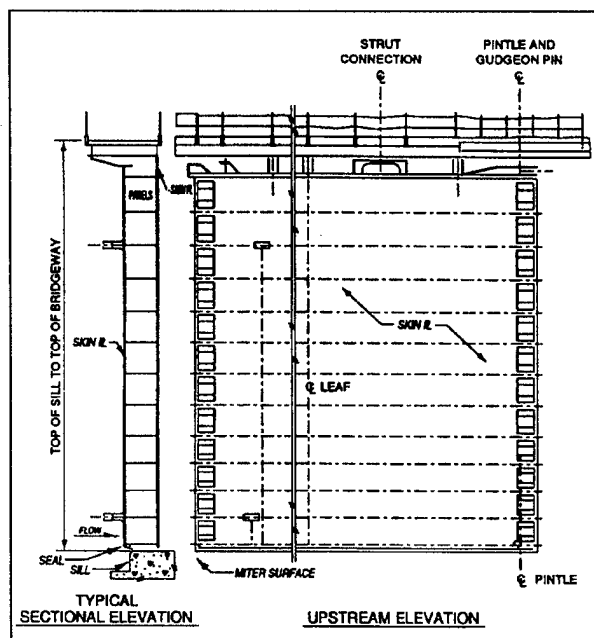


Figure B-2. Miter gate

*b. Submergible vertical-lift gate.* Submergible vertical-lift gates can sometimes be used to advantage at the upstream end of a lock. If the lift is high enough, a single leaf gate can be designed so that when it is lowered it drops down along the downstream vertical face of the upstream sill block. If the lift is not as great as the upstream sill depth, the gate may have two leaves that telescope together when they are lowered. It is not advisable to try to use a submergible vertical-lift gate in a situation where the leaf or leaves would have to rest in a bottom recess when the gate is lowered. Debris and silt would cause operation problems and lead to high maintenance costs. A vertical-lift gate can be designed to resist reverse head as well as direct head and can be designed to operate under either direct head or reverse head. The disadvantages are high maintenance and operation costs, difficulty in controlling skew and misalignment, and greater vulnerability to damage from collision than miter gates. Figure B-3 shows a typical submergible double-leaf, vertical-lift gate.

*c. Overhead vertical-lift gate.* The overhead vertical-lift gate has been used as the downstream gate at several locks where the lift is great enough to provide sufficient overhead clearance when the gate is in the raised

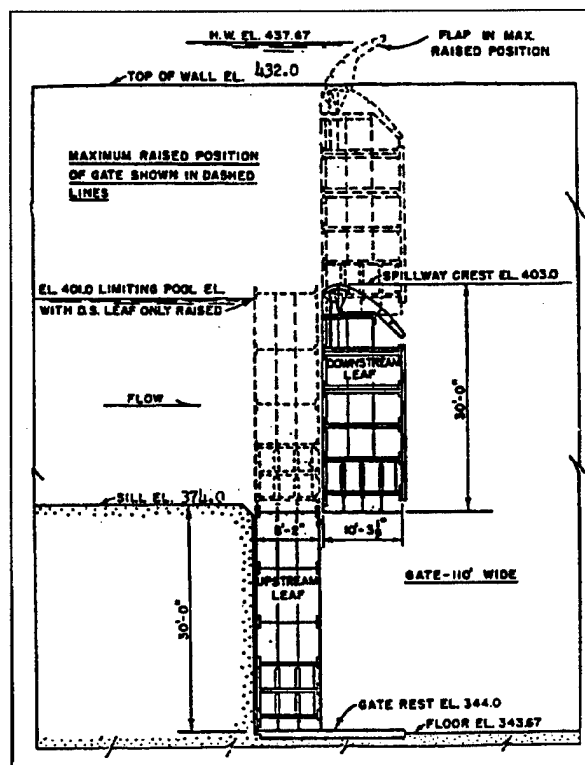


Figure B-3. Submergible vertical-lift gate

position. This type of gate has been used at the downstream end of the John Day, Ice Harbor, and Lower Monumental Locks. Overhead lift gates at these locks are very rugged and heavy. They possess the same general advantages as the submergible lift gates, but require a longer operation time--2 to 3 min. Operation and maintenance problems are not as great with overhead lift gates as with submergible gates. Figure B-4 shows a typical overhead vertical lift gate.

*d. Submergible tainter gate.* Submergible tainter gates have the same advantages as submergible lift gates, but are subject to the same limitations with regard to their use in a low- or medium-lift situation. The lift must be great enough to permit the gate to submerge to below the sill without resting directly on the lock floor. There are fewer operating and maintenance problems with submergible tainter gates than with vertical-lift gates. A typical submergible tainter lock gate is shown in Figure B-5.

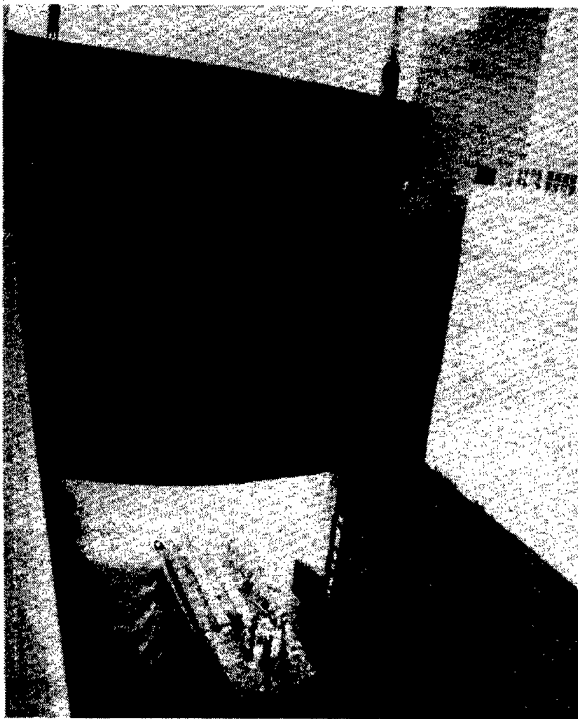


Figure B-4. Overhead vertical-lift gate

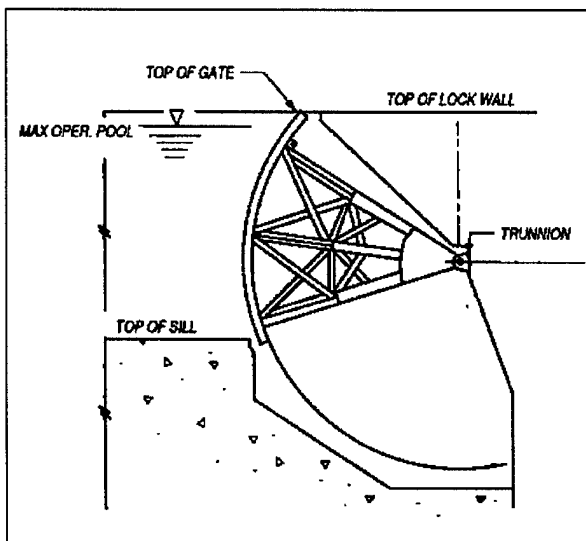


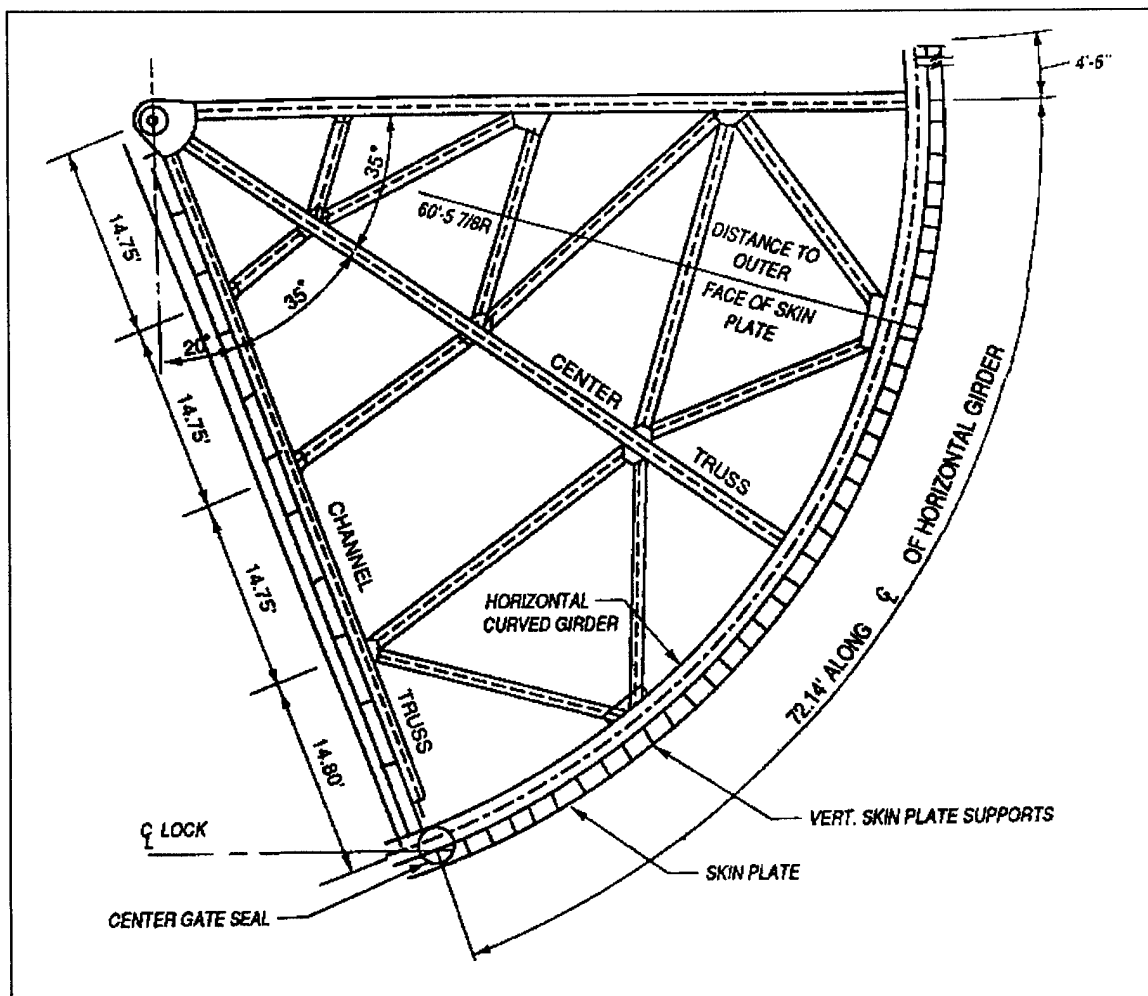
Figure B-5. Submersible tainter gate

e. *Vertical axis sector gates.* A vertical axis lock sector gate, like a miter gate, requires two gates at each end to effect closure of a lock chamber. Sector gates might be compared to a pair of tainter gates where the trunnions are mounted on a vertical axis. Sector gates are used in pairs and are designed to rotate around a vertical axis and meet at the center line of the lock chamber. Since the hydrostatic pressure is toward the gate axis, there is very little unbalanced hydraulic force opposing opening or closing under any condition of head. Figure B-6 shows a plan of a typical sector gate. Since sector gates can be opened or closed under a head, they can be used as a means of filling and emptying locks with very low lifts. Sector gates can be designed to withstand head from either direction and are very useful at a tidal lock or at any situation where reversal of head occurs. The two principal disadvantages are their cost and the amount of horizontal space required.

f. *Rolling gate.* A rolling gate consists of a structural steel frame with a skin plate, arranged to roll horizontally across the lock chamber from a recess in one lock wall. The structure moves on flanged wheels riding on rails embedded in the lock sill. When the gate is in the closed position, each end extends into a recess in each wall. When the gate is opened, it is pulled back into a recess in one wall that is long enough to receive the entire gate length. This type of gate was used in early canalization of the Ohio River before miter gates were developed that span 110-ft-wide locks. Several other early lock projects used this type of gate, but it has been entirely supplanted by other gate types in recent years. Rolling gates are still being used on recent large lock projects in Europe. Use of this type of gate complicates design of a filling system.

g. *Tumbler gate.* A tumbler gate is a single gate leaf with a horizontal hinge across the lock sill. In the open position, the leaf lies flat on the bottom of the lock chamber. To close the gate, the free edge of the gate is pulled upward in an arc and is retained in the vertical position by a locking mechanism. There is only one CE lock that uses this type of gate, and this design is considered to be obsolete.

h. *Rising sector gate.* The rising sector gate is a relatively new gate design. It is currently being used in Europe for locks that are approximately 75 ft wide and also as a flood barrier gate in England. This type of gate is essentially a segment of a circle attached to horizontal axis trunnion arms mounted on pivots at each end. When the gate is in the raised position, the curved



**Figure B-6. Sector gate**

surface of the segment closes the space between the sill and the water surface. When the gate is lowered, it is rotated 90 deg so that the segment then occupies a recess in the sill. In this position the gate causes no obstruction to traffic. Since this gate is untried for large locks, its reliability, usefulness, and cost are unknown.

### Section III Culvert-to-Chamber Designs

#### B-4. General

The categories and descriptions presented here and referenced by acronym in Section IV are qualitative rather than detailed. Details are available from design memoranda and drawings retained at the pertinent CE District or Division office. The designs are first subdivided into

“end” systems and “culvert” systems. For end systems the filling and emptying flow passages are independent and are normally located in or around the upper gate (filling) and lower gate (emptying). For culvert systems the flow passages are connected so that discharge ports for filling become intake ports for emptying. Within each of these two divisions, specific design concepts are identified, labeled by acronym, and briefly described.

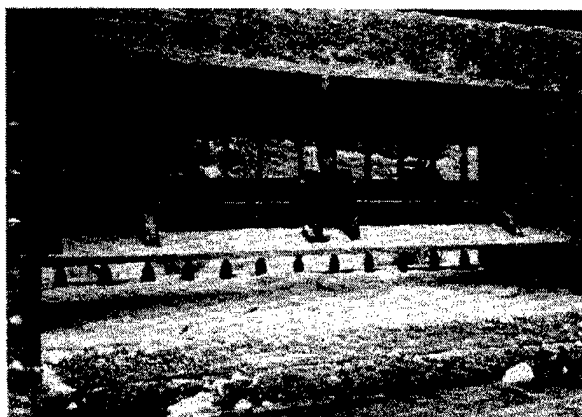
#### B-5. End Systems

Six different types of end systems are used.

*a. Valves in gates and lock walls.* Ports through the chamber gates (miter, vertical lift, or rolling) or lock walls are equipped with valves (slide or butterfly) that can be opened to let water into or out of the chamber.

Figure B-7 shows a view of a miter gate with butterfly valves. Acronyms are

- (1) BG = butterfly valve(s) in gate
- (2) VG = other type valve(s) in gate
- (3) BW = butterfly valve(s) in wall
- (4) CW = cylinder valve(s) in wall



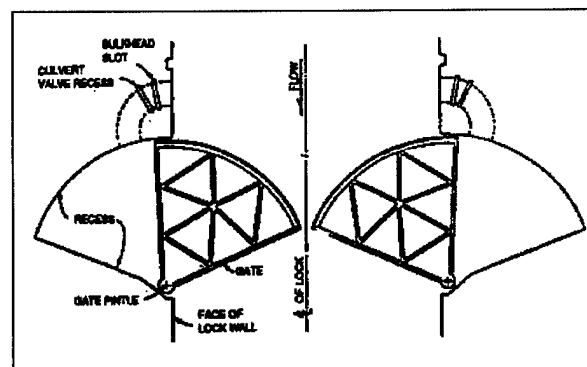
**Figure B-7. Miter gate with butterfly valves**

*b. Loop culverts.* Culverts with valves, which conduct flow around the gates, are placed in the upper and lower gate blocks. The lock is filled or emptied by operating the valves. Locks with passageways and valves in the sill (below the gate) are also in operation. Acronyms are

- (1) LC = loop culvert
- (2) LCSG = loop culvert and sector gate (dual system)

*c. Sector gates.* Sector gate locks have been used for recent very-low-lift lock projects. Vermilion Lock, currently under construction, is a suggested design option in the main text. The acronym is SG = sector gate. A dual loop culvert and sector gate system (LCSG) is shown in Figure B-8.

*d. Submergible vertical-lift gate.* Several locks have upper submergible vertical-lift gates. Their use for filling has not been found practical because of time and performance factors. Their use to augment filling and to pass ice and debris at high-lift projects has been of benefit. No acronym is required.



**Figure B-8. Sector gate and loop culvert system**

## B-6. Culvert Systems

There are five general types of culvert lock designs in operation. The objective in each design is to distribute the flow into and out of the lock chamber evenly throughout the entire operation so that filling and emptying are smooth (minimum of surface turbulence and currents) and rapid.

*a. Side port.* This culvert-to-chamber system is the most common CE design and is used for lifts up to about 40 ft. Performance and details are presented in the main text as a suggested design type. The modification for temporary very-low-lift locks uses one flume (rather than culverts) along one side of the lock chamber. This expedient design is also a suggested type for very specific design constraints and is also discussed in the main text. Acronyms are

- (1) SP = side-port system
- (2) SPF = side ports with adjacent flume

*b. Multiport system.* This system was developed by the Tennessee Valley Authority and is very similar to a conventional wall culvert side-port system. It differs primarily in having much smaller sized and a much greater number of ports. The port flow during filling is into a trench below the lock floor. CE design and operational experience and hydraulic model tests indicate that this system is comparable to a wall culvert side-port system in that hydraulic chamber characteristics and costs are about the same. Maintenance problems associated with size and number of ports have resulted in multiport systems being rejected for recent designs. The acronym is mp = multiport system.



*c. Centered lateral manifold systems.* These systems have lateral manifolds extending transversely across the lock chamber floor centered near the midpoint in the chamber. Interlaced systems for two-culvert filling and single-culvert systems are recent designs. These two systems are suggested options for low-lift locks as are side-port systems (*a* above). Similar layouts have been used for high-lift locks but because of chamber oscillation, culvert boundary cavitation, and related problems, are not suggested for new designs. Large geometric variations in size and shape of baffles, ports, and culverts have been tested in unsuccessful attempts to make these types of systems function well for high-lift projects. Acronyms are

- (1) BLC = centered lateral system modified for high lift
- (2) BL2 = two-culvert centered lateral system
- (3) BL1 = one-culvert centered lateral system

*d. Split lateral manifold system.* The transverse or lateral manifolds on the lock floor are not intermeshed. They are arranged so that one wall culvert connects with one group of laterals in one end of the lock; another group of laterals in the opposite end of the lock is connected to the opposite wall culvert. This system achieves a better distribution of flow than the intermeshed system, especially for medium and high lifts. The most dramatic operational disadvantage arises from the fact that any lack of synchronization of the filling valves causes unbalanced flow that creates dangerous surges. Two potentially serious accidents have occurred because of the failure of filling valves to open in unison. In these incidents, tows in the lock broke their mooring lines and only timely and immediate action by vessels' crews prevented serious consequences. Fail-safe devices have been developed that will stop movement of both valves if a difference in opening of more than 0.5 ft develops at any time during valve opening. Although these devices reduce nonsynchronous valving, unacceptable chamber oscillations still occur; and filling with one valve when the other is out of service presents serious operational problems. For these reasons and because cost difference between a split lateral system and a bottom longitudinal system (*e* below) is not great, the split lateral system is no longer used. The acronym is SBLC = split bottom lateral manifold system.

*e. Longitudinal manifold systems.* Five arrangements are currently in operation; the two systems suggested for new designs are the four-manifold type (Plate 3-7), and the eight-manifold type (Plate 3-8). For these designs a horizontal pier causes a vertical bifurcation of the flow; the intent is to achieve equal flow at each manifold. Systems with vertical piers, such as shown in Figure B-9, are sensitive to pier location as far as flow division is concerned and are susceptible to cavitation damage at the short radius bends.

#### Section IV

#### Existing Locks

### B-7. Inventory

An inventory of existing CE locks is included in Table B-1; a computer-based listing is available as described in EP 1105-2-11. Two locks under construction are a replacement lock at Lock and Dam 26, Mississippi River, and Vermilion Lock, Gulf Intracoastal Waterway. A summary of acronyms for filling system type as used in Table B-1 follows; a preceding \* represents recent design types.

- a. G* = butterfly valve(s) in gate
- b. VG* = other valve(s) in gate (slide valves normally)
- c. BW* = butterfly valve(s) in wall
- d. CW* = cylinder valve(s) in wall
- e. LC* = loop culvert(s)
- f. LCSG* = loop culvert(s) and sector gate
- g. \*SG* = sector gates
- h. \*SP* = side ports
- i. \*SPF* = side ports with flume
- j. MP* = multiport system
- k. \*BL1* = centered lateral-manifolds; one culvert

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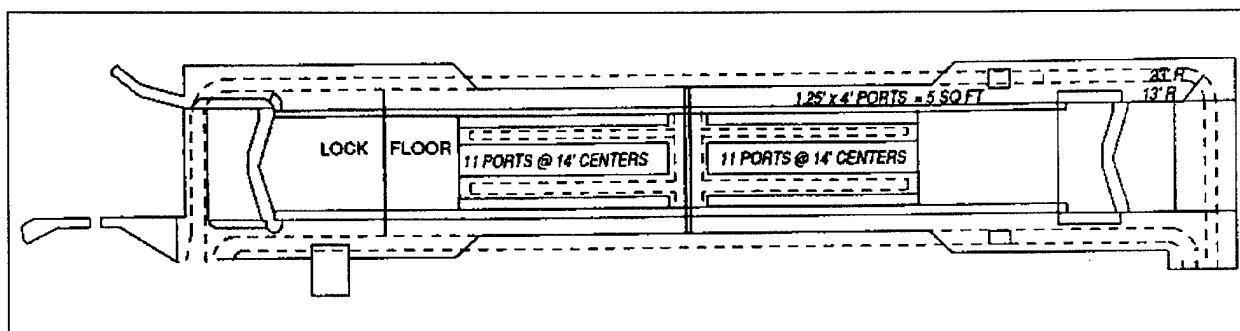


Figure B-9. Horizontally split bottom longitudinal system

- |  |  |
|--|--|
| <p><i>l.</i> *BL2 = centered lateral-manifolds; two culverts</p> <p><i>m.</i> BLC = centered lateral-manifolds; high-lift modified</p> <p><i>n.</i> SBLC = split lateral-manifolds</p> <p><i>o.</i> OC = longitudinal centered and ported culvert</p> <p><i>p.</i> VB4 = vertical flow dividers; four longitudinal manifolds</p> <p><i>q.</i> VB8 = vertical flow dividers; eight longitudinal manifolds</p> | <p><i>r.</i> *HB4 = horizontal flow dividers; four longitudinal manifolds</p> <p><i>s.</i> *HB8 = horizontal flow dividers; eight longitudinal manifolds</p> |
|--|--|

#### B-9. Historical Development

A chart showing the historical change in design practice is included as Figure B-10.

Table B-1  
U.S. Army Corps of Engineers Navigation Locks and Dams

Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
Alabama-Coosa Rivers, AL Claiborne Lock and Dam Millers Ferry Lock and Dam Jones Bluff Lock and Dam	Claiborne, AL Camden, AL Benton, AL	1973 1969 1974	84 84 84	600 600 600	30 45 45	VB4 VB4 VB4
Allegheny River, PA and NY Lock and Dam No. 2 Lock and Dam No. 3 Lock and Dam No. 4 Lock and Dam No. 5 Lock and Dam No. 6 Lock and Dam No. 7 Lock and Dam No. 8 Lock and Dam No. 9	Aspinwall, PA Cheswick, PA Natrona, PA Freeston, PA Clinton, PA Kittanning, PA Templeton, PA Rimer, PA	1934 1934 1927 1927 1928 1931 1937 1938	56 56 56 56 56 56 56 56	360 360 360 360 360 360 360 360	11 13 10 12 12 13 18 22	SP SP SP SP SP SP SP SP
Apalachicola, Chattahoochee, and Flint Rivers, GA and FL Jim Woodruff Lock and Dam George W. Andrews Lock and Dam Walter F. George Lock and Dam	Chattahoochee, FL Columbia, GA Fort Gaines, GA	1957 1963 1963	82 82 82	450 450 450	33 25 88	SP SP SBLC
Atlantic Intracoastal Waterway Albermarle and Chesapeake Canal Rt: Great Br. Lock Dismal Swamp Canal Route: Deep Creek Lock South Mills Lock	Great Bridge, VA Deep Creek, VA South Mills, NC	1932 1940 1941	75 52 52	600 300 300	3 12 12	LC VG VG
Bayou Teche, LA Berwick Lock Keystone Lock	Berwick, LA New Iberia, LA	1951 1913	45 36	300 160	7 8	SG SP
Black Rock Channel and Tonawanda Harbor, NY Black Rock Lock	Buffalo, NY	1914	68	625	5	
Black Warrior, Warrior, and Tombigbee Rivers, AL Coffeeville (Jackson) Lock and Dam Demopolis Lock and Dam Warrior Lock and Dam Wm. Bacon Oliver Lock and Dam Holt Lock and Dam John Hollis Bankhead Lock and Dam Gainesville Lock and Dam	Coffeeville, AL Demopolis, AL Eutaw, AL Tuscaloosa, AL Holt, AL Adger, AL Gainesville, AL	1965 1962 1962 1940 1969 1915	110 110 110 95 110 52 110	600 600 600 460 600 286 600	34 40 22 28 68 68	SP BL2 SP SP BLC VB4 SP

(Sheet 1 of 9)

T. 1 (Continued)

Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
Aliceville Lock and Dam	Aliceville, AL		110	600		SP
Columbus Lock and Dam	Columbus, MS		110	600		SP
Aberdeen Lock and Dam	Aberdeen, MS		110	600		SP
Lock and Dam A	Amory, MS		110	600		SP
Lock and Dam B	Amory, MS		110	600		SP
Lock and Dam C	Fulton, MS		110	600	25	SP
Lock and Dam D	Fulton, MS		110	600		SP
Lock and Dam E	Fulton, MS		110	600		SP
Bay Springs Lock and Dam	Fulton, MS		110	600		HB4
Canaveral Harbor, FL						
Canaveral Lock	Cocoa, FL	1965	90	600	3	
Cape Fear River, NC						
Lock and Dam No. 1	Kings Bluff, NC	1934	40	200	11	BG
Lock and Dam No. 2	Browns Landing, NC	1917	40	200	9	BG
William O. Huskie Lock and Dam	Tolars Landing, NC	1935	40	300	9	BG
Central and Southern Florida						
S-61 Lock	St. Cloud, FL	1963	30	90	2	SG
S-65 Lock	Frostproof, FL	1964	30	90	6	SG
S-65A Lock	Avon Park, FL	1967	30	90	6	SG
S-65B Lock	Sebring, FL	1965	30	90	6	SG
S-65C Lock	Sebring, FL	1965	30	90	7	SG
S-65D Lock	Okeechobee, FL	1964	30	90	6	SG
S-65E Lock	Okeechobee, FL	1964	30	90	5	SG
Columbia River, OR and WA						
Bonneville Lock and Dam	Bonneville, OR	1938	76	500	65	OC
The Dalles Lock and Dam	The Dalles, OR	1957	86	675	88	SBLC
John Day Lock and Dam	Rufus, OR	1968	86	669	110	BLC
McNary Lock and Dam	Umatilla, OR	1953	86	683	75	BLC
Cross-Florida Barge Canal						
Inglis Lock, Dam and Spillway	Inglis, FL	1968	84	600	28	SP
Eureka Lock and Dam		1971	84	600	20	SP
Henry H. Buckman Lock	Palatka, FL	1972	84	600	20	SP
Cumberland River, KY and TN						
Lock and Dam	Kuttawa, KY	1964	110	800	57	SBLC
Cheatham Lock and Dam	Ashland City, TN	1959	110	800	26	SP
Old Hickory Lock and Dam	Old Hickory, TN	1957	84	400	60	MP
Cordell Hull Dam and Reservoir	Carthage, TN	1973	84	400	59	MP

(Sheet 2 of 9)

Table B-1 (Continued)

Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
<b>Fox River, WI</b>						
DePere Lock	DePere, WI	1936	36	146	9	MP
Little Kaukauna Lock	DePere, WI	1936	36	146	7	BG
Rapid Croche Lock	Wrightstown, WI	1934	36	146	8	BG
Kaukauna Fifth Lock	Kaukauna, WI	1898	36	144	9	BG
Kaukauna Fourth Lock	Kaukauna, WI	1879	37	144	10	BG
Kaukauna Third Lock	Kaukauna, WI	1879	37	144	10	BG
Kaukauna Second Lock	Kaukauna, WI	1903	35	144	11	BG
Kaukauna First Lock	Kaukauna, WI	1883	35	144	11	BG
Kaukauna Guard Lock	Kaukauna, WI	1891	40	144		
Little Chute Combined Lock						
Lower						
Upper						
Little Chute, Second Lock	Little Chute, WI	1879	35	147	11	BG
Little Chute, First (Guard) Lock	Little Chute, WI	1879	36	144	11	BG
Cedars Lock	Little Chute, WI	1881	35	144	14	BG
Appleton Fourth Lock	Little Chute, WI	1904	35	144	7	BG
Appleton Third Lock	Little Chute, WI	1888	35	144	10	BG
Appleton Second Lock	Appleton, WI	1907	35	144	8	BG
Appleton First Lock	Appleton, WI	1900	35	144	9	BG
Menasha Lock	Appleton, WI	1901	35	145	10	BG
	Appleton, WI	1884	35	145	10	BG
	Menasha, WI	1899	35	144	8	BG
<b>Freshwater Bayou Lock, LA</b>	Intracoastal City, LA	1968	84	600		SG
<b>Green and Barren Rivers, KY</b>						
Green River:						
Lock and Dam No. 1	Spottsville, KY	1956	84	600	12	SP
Lock and Dam No. 2	Calhoun, KY	1956	84	600	14	SP
Lock and Dam No. 3	Rochester, KY	1836	36	138	17	VG
Lock and Dam No. 4	Woodbury, KY	1839	35	138	16	VG
<b>Barren River:</b>						
Lock and Dam No. 1	Greencastle, KY	1934	56	360	15	
<b>Gulf Intracoastal Waterway</b>						
Inner Harbor Navigation Channel Lock	New Orleans, LA	1923	75	640	9	
Harvey Lock	Harvey, LA	1935	75	425	10	SP
Algiers Lock	Algiers, LA	1956	75	800	10	SG

(Sheet 3 of 9)

Tab. (Continued)						
Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
Bayou Boeuf Lock	Morgan City, LA	1956	75	1,156	6	SG
Bayou Sorrel Lock	Plaquemine, LA	1952	56	797	10	SG
Port Allen Lock	Port Allen, LA	1961	84	1,202	5	SP
Vermilion Lock	Abbeville, LA	1934	56	1,182	3	LCSG
Calcasieu Lock	Lake Charles, LA	1950	75	1,206	6	SG
Colorado River, TX						
East Lock	Matagorda, TX	1954	75	1,200	5	
West Lock	Matagorda, TX	1954	75	1,200	5	
Hudson River, NY						
Troy Lock and Dam	Troy, NY	1917	44	493	17	SP
Illinois Waterway, IL						
LaGrange Lock and Dam	Beardstown, IL	1939	110	600	10	
Peoria Lock and Dam	Peoria, IL	1939	110	600	11	SP
Starved Rock Lock and Dam	Utica, IL	1933	110	600	19	SP
Marseilles Lock	Marseilles, IL	1933	110	600	24	SP
Dresden Island Lock and Dam	Morris, IL	1933	110	600	22	SP
Brandon Road Lock and Dam	Joliet, IL	1933	110	600	34	SP
Lockport Lock	Lockport, IL	1933	110	600	40	SP
Thomas J. O'Brien Lock and Dam	Chicago, IL	1960	110	1,000	2	LCSG
Inland Route, MI						
Crooked River Lock and Weir	Alanson, MI	1967	17.8	66	66	
Kanawha River, WV						
Winfield Lock and Dam	Winfield, WV	1937	56	360	28	SP
Marmet Lock and Dam	Marmet, WV	1934	56	360	24	SP
London Lock and Dam	London, WV	1934	56	360	24	SP
Kentucky River, KY						
Lock and Dam No. 1	Carrollton, KY	1839	38	145	8	BG
Lock and Dam No. 2	Lockport, KY	1939	38	145	14	BG
Lock and Dam No. 3	Gest, KY	1844	38	145	13	BG
Lock and Dam No. 4	Frankfort, KY	1844	38	145	13	BG
Lock and Dam No. 5	Tyrone, KY	1844	38	145	15	BG
Lock and Dam No. 6	High Bridge, KY	1891	52	147	14	CW
Lock and Dam No. 7	High Bridge, KY	1897	52	147	15	BW
Lock and Dam No. 8	Camp Nelson, KY	1900	52	146	19	BW
Lock and Dam No. 9	Valley View, KY	1907	52	148	17	CW

(Sheet 4 of 9)

Table B-1 (Continued)

Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
Lock and Dam No. 10	Ford, KY	1907	52	148	17	CW
Lock and Dam No. 11	Irvine, KY	1906	52	148	18	CW
Lock and Dam No. 12	Ravenna, KY	1910	52	148	17	CW
Lock and Dam No. 13	Willow, KY	1915	52	148	18	CW
Lock and Dam No. 14	Heidelberg, KY	1917	52	148	17	CW
Lake Washington Ship Canal						
Hiram M. Chittenden Locks	Seattle, WA	1916	80	760	26	SP
Large Lock	Seattle, WA		28	123	26	SP
Small Lock						
McClellan-Kerr Arkansas River, AR and LA						
Norrell Lock and Dam	Arkansas Post, AR	1967	110	600	30	SP
Lock No. 2	Arkansas Post, AR	1967	110	600	20	SP
Lock and Dam No. 3	Grady, AR	1968	110	600	20	SP
Lock and Dam No. 4	Pine Bluff, AR	1968	110	600	14	SP
Lock and Dam No. 5	Redfield, AR	1968	110	600	17	SP
David D. Terry Lock and Dam	Little Rock, AR	1968	110	600	18	SP
Murray Lock and Dam	Little Rock, AR	1969	110	600	16	SP
Toad Suck Ferry Lock and Dam	Conway, AR	1969	110	600	19	SP
Lock and Dam No. 9	Morrilton, AR	1969	110	600	19	SP
Lock and Dam No. 13	Fort Smith, AR	1969	110	600	19	SP
Dardanelle Lock and Dam	Russellville, AR	1969	110	600	54	HBA
Ozark Lock and Dam	Ozark, AR	1975	110	600	34	SP
W. D. Mayo Lock and Dam	Fort Smith, AR	1970	110	600	20	SP
Chouteau Lock and Dam	Mustogee, OK	1970	110	600	21	SP
Newt Graham Lock and Dam	Inola, OK	1970	110	600	21	SP
Robert S. Kerr Lock and Dam and Reservoir	Salisbury, OK	1970	110	600	48	BLC
Webbers Falls Lock and Dam	Webbers Falls, OK	1970	110	600	30	SP
Mississippi River Between Ohio and Missouri Rivers						
Lock and Dam No. 27	Granite City, IL	1963	110	1,200	21	SP
Lock and Dam No. 26	Alton, IL	1938	110	600	21	SP
Lock and Dam No. 25	Cap Au Gris, MO	1939	110	360	24	SP
Lock and Dam No. 24	Clarksville, MO	1940	110	600	15	SP
Lock and Dam No. 22	Saverton, MO	1938	110	600	15	SP
Lock and Dam No. 21	Quincy, IL	1938	110	600	10	SP
Lock and Dam No. 20	Canton, MO	1936	110	600	10	SP

(Sheet 5 of 9)

Table (Continued)

Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
Lock and Dam No. 19	Keokuk, IA	1913	110	358	38	
		1957	110	1,200	38	
Lock and Dam No. 18	Burlington, IA	1937	110	600	10	SP
Lock and Dam No. 17	New Boston, IL	1939	100	600	9	SP
Lock and Dam No. 16	Muscatine, IA	1937	110	600	9	SP
Lock and Dam No. 15	Rock Island, IL	1934	110	600	16	SP
			110	360	16	SP
Lock and Dam No. 14	LeClaire, IA	1922	80	320	11	SP
	LeClaire, IA	1939	110	600	11	SP
Lock and Dam No. 13	Clinton, IA	1939	110	600	11	SP
Lock and Dam No. 12	Bellevue, IA	1938	110	600	9	SP
Lock and Dam No. 11	Dubuque, IA	1937	110	600	11	SP
Lock and Dam No. 10	Guttenberg, IA	1936	110	600	8	SP
Lock and Dam No. 9	Lynxville, WI	1938	110	600	9	SP
Lock and Dam No. 8	Genos, WI	1937	110	600	11	SP
Lock and Dam No. 7	Dresbach, MN	1937	110	600	8	SP
Lock and Dam No. 6	Trempealeau, WI	1936	110	600	6	SP
Lock and Dam No. 5A	Winona, MN	1936	110	600	5	SP
Lock and Dam No. 5	Minneiska, MN	1935	110	600	9	SP
Lock and Dam No. 4	Alma, WI	1935	110	600	7	SP
Lock and Dam No. 3	Red Wing, MN	1938	110	600	8	SP
Lock and Dam No. 2	Hastings, MN	1930	110	600	12	SP
Lock and Dam No. 1	Minneapolis-St. Paul	1948	56	400	36	SP
		1932	56	400	36	SP
		1917	56	400	27	BL2
St. Anthony Falls Lower Lock and Dam	Minneapolis, MN	1963	56	400	49	BLC
St. Anthony Falls Upper Lock and Dam	Minneapolis, MN					
Monongehela River, PA and WV						
Lock and Dam No. 2	Braddock, PA	1951	56	360	9	SP
		1953	110	720	9	SP
Lock and Dam No. 3	Elizabeth, PA	1907	56	360	8	SP
		1907	56	720	8	SP
Lock and Dam No. 4	Monessen, PA	1932	56	360	17	SP
		1932	56	720	17	SP
Maxwell Locks and Dam	Maxwell, PA	1965	84	720	20	BL2
		1965	84	720	20	BL2
Lock and Dam No. 7	Greensboro, PA	1926	56	360	15	SP
Lock and Dam No. 8	Point Marion, PA	1959	56	360	19	SP
Morgantown Lock and Dam	Morgantown, WV	1960	84	600	17	SP
Hildebrand Lock and Dam	Morgantown, WV	1960	84	600	21	SP
Opekiska Lock and Dam	Morgantown, WV	1964	84	600	22	SP

(Sheet 6 of 9)



Table B-1 (Continued)

Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
Ohio River Lock and Dam No. 53	Mound City, IL	1970	110	1,200	13	SPF
Lock and Dam No. 52	Brookport, IL	1972	110	1,200	12	SPF
Smithland Lock and Dam	Bobcoda, IL		110	1,200	22	SP
			110	1,200	22	SP
Uniontown Locks and Dam	Uniontown, KY	1975	110	1,200	22	BL2
			110	600	22	BL1
Newburgh Locks and Dam	Newburgh, IN	1975	110	1,200	16	BL2
			110	600	16	BL1
Cannelton Locks and Dam	Cannelton, IN	1972	110	1,200	25	SP
			110	600	25	BL1
McAlpine Locks and Dam	Louisville, KY	1961	110	1,200	37	BL2
		1921	110	600	37	SP
		1930	56	360	37	SP
Markland Locks and Dam	Markland, IN	1963	110	1,200	35	BL2
		1963	110	600	35	BL1
Capt. Anthony Meldahl Locks and Dam	Chilo, OH	1962	110	1,200	30	BL2
		1962	110	600	30	BL1
Greenup Locks and Dam	Greenup, KY	1962	110	1,200	30	BL2
			110	600	30	BL1
Gallipolis Locks and Dam	Hogsett, WV	1937	110	600	23	SP
			110	360	23	SP
Racine Locks and Dam	Letart Falls, OH	1970	110	1,200	22	SP
			110	600	22	BL1
Belleville Locks and Dam	Reedsville, OH	1969	110	1,200	22	BL2
			110	600	22	BL1
Willow Island Locks and Dam	Waverly, WV	1973	110	1,200	20	SP
			110	600	20	BL1
Hannibal Locks and Dam	New Martinsville, WV	1972	110	1,200	21	SP
			110	600	21	BL1
Pike Island Locks and Dam	Warwood, WV	1965	110	1,200	18	SP
			110	600	18	BL1
New Cumberland Locks and Dam	Stratton, OH	1961	110	1,200	21	SP
			110	600	21	BL1
Montgomery Island Locks and Dam	Industry, PA	1936	110	600	18	SP
			56	360	18	SP
Dashields Locks and Dam	Glenwillard, PA	1929	110	600	18	SP
			56	360	10	SP
Emsworth Locks and Dam	Emsworth, PA	1921	110	600	18	SP
			56	360	18	SP

(Sheet 7 of 9)

Tab. (Continued)						
Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
Okeechobee Waterway, FL						
St. Lucie Lock and Dam	Stuart, FL	1941	50	250	13	SG
Moore Haven Lock	Moore Haven, FL	1953	50	250	2	
Ortona Lock and Dam	LaBelle, FL	1937	50	250	11	
W. P. Franklin Lock and Control Structure	Fort Myers, FL	1965	56	400	3	
Old River, LA						
Old River Lock	Simmesport, LA	1963	75	1,200	35	SP
Ouachita and Black Rivers, AR						
Jonesville Lock and Dam	Jonesville, LA	1972	84	600	30	SP
Columbia Lock and Dam	Columbia, LA	1972	84	600	18	SP
Lock and Dam No. 6	Falsenthal, AR	1923	55	268	10	SP
Lock and Dam No. 8	Callion, AR	1926	55	268	14	SP
Pearl River, MS and LA						
Lock 1	Pearl River, LA	1951	65	310	17	LC
Lock 2	Bush, LA	1951	65	310	15	LC
Lock 3	Sun, LA	1951	65	310	11	LC
Sacramento River, CA						
Barge Canal Lock	West Sacramento, CA	1961	86	600	4	SG
Snake River, WA						
Ice Harbor Lock and Dam	Pasco, WA	1962	86	665	100	SBLC
Lower Monumental Lock and Dam	Walla Walla, WA	1969	86	666	98	SBLC
Little Goose Lock and Dam	Dayton, WA	1970	86	668	98	SBLC
Lower Granite Lock and Dam	Almota, WA	1975	86	674	100	HB8
St. Marys River, MI						
South Canal	Sault Ste. Marie, MI	1943	80	800	22	
MacArthur Lock	Sault Ste. Marie, MI	1968	110	1,200		SP
Poe Lock						
North Canal						
Davis Lock	Sault Ste. Marie, MI	1914	80	1,350	22	OC
Sabin Lock	Sault Ste. Marie, MI	1919	80	1,350	22	OC

(Sheet 8 of 9)

(Sheet 8 of 9)

Table B-1 (Concluded)

Project	Community in Vicinity	Year Opened	Width of Chamber ft	Locks Usable Length ft	Lift at Normal Pool ft	Filling System Acronym (Para B-7)
Savannah River, GA Savannah River Lock and Dam	Augusta, GA	1936	56	360	15	SP
Tennessee River, TN, AL, MS, and KY Kentucky Lock and Dam	Gilbertsville, KY	1944	110	600	56	SP
Pickwick Landing Lock and Dam	Hamburg, TN	1937	110	600	55	SP
Wilson Lock and Dam: Main Lock	Florence, AL	1959	110	600	94	VB8
Auxiliary Lock	Florence, AL	1927	60	292	47	SP
			60	300	47	OC
General Joe Wheeler Lock and Dam Main Lock	Florence, AL	1963	110	600	48	SP
Auxiliary Lock	Florence, AL	1962	60	400	48	SP
Guntersville Lock and Dam Main Lock	Guntersville, AL	1965	110	600	39	SP
Auxiliary Lock	Guntersville, AL	1939	60	360	39	SP
Nickajack Lock and Dam	Chattanooga, TN	1967	110	600	39	SP
Chickamauga Lock and Dam	Chattanooga, TN	1940	60	360	49	SP
Watts Bar Lock and Dam	Breeden, TN	1942	60	360	58	SP
Fort Loudon Lock and Dam	Lenoir City, TN	1943	60	360	72	MP
Melton Hill Lock and Dam (Clinch River)	Kingston, TN	1963	75	400	54	MP
Willamette River at Willamette Falls, OR Lock No. 1	Oregon City, OR	1872	37	175	20	VG
Lock No. 2	Oregon City, OR	1872	37	175	10	VG
Lock No. 3	Oregon City, OR	1872	37	175	10	VG
Lock No. 4	Oregon City, OR	1872	37	175	10	VG
Guard Lock	Oregon City, OR	1872	38	175	10	VG

(Sheet 9 of 9)

<u>Suggested Designs; New Projects</u>			<u>Usable Chamber Dimensions</u>		No. of Exist. <u>Locks</u>
<u>Project Lift</u>	<u>Symbol</u>	<u>Description</u>	<u>Width ft</u>	<u>Length(s) ft</u>	
Very low (0-10')	SG	Sector gate	30 75	90 800,1200	
		Other sizes			4
	SPF	Side-ports and flume (temporary locks)	110	1200	2
Low (10'-30/40')	SP	Side-port	110 110 84 56	1200 600 600 360	10 63 7 20
		Other sizes			28
	BL2	Centered lateral manifolds	10	1200	8
	BL1	One-sided lateral manifolds	110	600	12
<u>Horizontal Flow Dividers</u>					
High (Lift > 40')	HB4	Longitudinal 4 manifolds	110	600	1
	HB8	Longitudinal 8 manifolds	86	675	1
<u>Designs Obsolete and/or Defective</u>			<u>Unsuitable Design Situations</u>		
<u>Symbols</u>	<u>Description</u>				
BG, VG, BW, CW	Valves in gates and walls		All existing		44
LC, LCSG	Loop culvert variations		All existing		6
BLC	Centered lateral manifolds		Lifts > 40'		4
SBLC	Split lateral manifolds		All existing		7
VB4, VB8	Vertical flow dividers		All existing		5
Other Locks: Unreported/unusual sizes and types					19
Non-CE designs					16
Total listing = 268 Locks					

Figure B-10. Historical development of CE lock designs

## Appendix C Lock Hydraulic System Model and Prototype Study Data

### C-1. Introduction

The availability of data from CE hydraulic model and prototype investigations of navigation lock filling/emptying systems, as summarized in Table C-1, is given in Table 1 of Item P5. This information was obtained from a detailed review of 81 reports on model and prototype studies (1937 to 1984) by STP, BHL, and WES. Those reports are listed in Appendix A. The organization and use of Table 1, Item P5, are described in the following paragraphs.

**Table C-1**  
**Lock Hydraulic System Model and Prototype Study Data**

PAGE SEQUENCE FOR TABLE 1				
DESIGN AND OPERATIONAL VARIABLES	TEST REPORT COLUMN NUMBERS			
	01 TO 20	21 TO 45	46 TO 65	66 TO 90
11000 TO 11275	(1)	(2)	(3)	(4)
11300 TO 12290	(5)	(6)	(7)	(8)
12300 TO 13238	(9)	(10)	(11)	(12)
13240 TO 14180	(13)	(14)	(15)	(16)
14200 TO 15290	(17)	(18)	(19)	(20)
15300 TO 16260	(21)	(22)	(23)	(24)
16300 TO 16460 AND "NOTED ITEMS"	(25)	(26)	(27)	(28)
	FACING PAGES		FACING PAGES	

1. Select DESIGN and/or OPERATIONAL variable(s) of interest and note line number(s) (1100 to 16460).
2. Trace selected line(s) across appropriate tables and note which REPORTS (columns) contain TYPES OF DATA (T, O, Q, etc.) of interest.
3. See Appendix A for full titles of REPORTS.

### C-2. Design and Operational Variables

A list of 251 hydraulic design and operational variables or significant features of navigation locks was derived from a review of such items in several kinds of filling/emptying systems used in CE locks. This list is organized in an upstream-to-downstream order and has a numbering sequence for easier manipulation in a digital computer. The major divisions of the list include:

- 11000 INTAKE SYSTEM
- 12000 FILLING VALVE SYSTEM
- 13000 CULVERT-CHAMBER MANIFOLD
- 14000 LOCK CHAMBER
- 15000 EMPTYING VALVE SYSTEM
- 16000 OUTLET SYSTEM

A listing of operational variables is included with each major division in Table C-1 rather than in a separate division in order to group more closely the aspects of the lock operation with their related design features. The 22 "NOTED ITEMS" lines include special items peculiar to the specific projects and are identified in the notes at the end of Table C-1.

### C-3. Test Reports

Each column heading in Table C-1 includes a very brief identification of the project and a brief notation of the report number (full title in Appendix A). The reports are listed in chronological order of the report dates. The STP Report No. 46 contains six separate studies and is listed in six separate columns in Table C-1. This gives an apparent total of 86 reports. All the reports are available on loan from the WES Technical Library.

### C-4. Types of Data in Reports

The types of lock performance data available in each report and pertaining specifically or generally to the various design and operational features investigated are indicated by the following letter symbols in Table C-1:

T = time, curves, and/or tabulation of lock chamber filling and/or emptying, or actual valve motion in a few tests

O = overfill or overempty in lock chamber

- Q = culvert system discharge, or lock chamber rate-of-rise or rate-of-fall
- H = hawser force on tow in lock chamber, or in approach in a few tests
- D = tow displacement, unrestrained by hawsers
- V = local velocities in ports, approach channel, etc.
- C = surface currents, including vortices at intakes
- B = boils, or surface turbulence
- W = waves, or water-surface profiles in a few tests
- S = surges or oscillations
- I = internal flow pattern or flow distribution
- Z = local average piezometric pressures
- P = local transient or fluctuating pressures
- L = pressure losses or differences
- F = mechanical forces or torque
- A = vibration
- X = other data, usually air vent discharge.  
See last line of NOTED ITEMS at end of Table C-1

#### C-5. Comments

The following comments result from observations during the compilation of Table C-1 and may be of interest and/or assistance to users searching for available test data pertinent to their design problems.

a. Consideration of both the design and operational variables of the feature under investigation, both more general and more specific identification of the variables, and related items or systems in Table C-1 may aid in finding data that might otherwise be missed.

b. The listing of operational variables at "division level" in Table C-1 and the compilation process may have resulted in some inappropriate entries of types of data relative to the design variables. This would most likely occur where a report table or illustration includes several kinds of design and operational variables.

c. Culvert roof pressures just downstream from a valve were considered pertinent to, and listed under, 12230 (15230) FILLING (EMPTYING) VALVE SYSTEM, FLOW PASSAGE, ROOF EL, although a different variable may have been the primary consideration.

d. Surface currents at the intakes are listed under 11150 INTAKE SYSTEM, APPROACH, VORTEX CONTROL, although the vortex control may have been by valve operation or other feature rather than modification of the intake system.

e. Variable 14000 LOCK CHAMBER was given data references for nearly every citation involving lock chamber filling and emptying times and/or rates, hawser forces, surges, etc. Although there may not have been any design variations within the chamber, it is a location of primary interest for most aspects of lock operation.

#### C-6. Detailed Test Data Listings

Individual test report listings of the data locations within the reports are given in Item P5. An example list is given in Table C-2. The LINE NO'S correspond to those 251 numbers assigned to the design and operation variables. The TYPE OF DATA symbols correspond to those given in paragraph C-4 above. The FORMAT symbols are:

- T = numbered table
- P = numbered photograph
- D = numbered drawings (plates)
- F = numbered figures (covers all illustrations in STP reports)
- W = test paragraph (or page if unnumbered paragraphs) containing information not indicated by the tables, photographs, drawings, or figures.

SORTED DATA FILE NO E01SP019  
DATE 10/15/88  
PROJECT: PICKWICK  
DETAIL:         
REPORT: STP 19  
MISC:         
ENTRIES 275

SORTED DATA FILE NO E01SP018				
DATE 10/15/85				
PROJECT: PICKWICK				
DETAIL: REPORT: STP 19				
MISC: ENTRIES 275				
LINE NO.	TYPE OF DATA	FORMAT	LOCATION IN REPORT	
11300	I	F	10,11,12,16	13241
11300	I	F	10,11,12,16	13255
11300	I	F	10,11,12,16	13300
11300	I	F	10,11,12,16	13340
11300	I	F	10,11,12,16	13350
11300	I	F	10,11,12,16	13370
11300	I	F	10,11,12,16	14000
11450	I	F	10,20	14212
11450	I	F	10,20	14230
11450	I	F	10,20	14240
12110	I	F	20,22,23,24,26,26,27,28,30,31	15100
12200	I	F	20,31,32	15110
12200	I	F	20,31,32	15200
12230	I	F	20,31,32	15270
12270	I	F	20,31,32	15280
12280	I	F	20,31,32	15300
12330	I	F	20,31,32	16200
12350	I	F	20,31,32	16230
12370	I	F	20,31,32	16231
13100	I	F	20,31,32	16252
13170	I	F	20,31,32	16400
13200	I	F	20,31,32	16400
13240	I	F	20,31,32	16400

**30 Jun 95**

The LOCATION IN REPORT numbers and letters are those of the pertinent tables, photographs, drawings, figures, and/or paragraphs in that particular report.

#### **C-7. Instruction**

In addition to the indicated tables, photographs, drawings, and/or figures having data pertinent to a specific design and/or operational variable, the user should refer to those parts of the text where these data items are discussed. The comment in subparagraph C-5*b* above also applies to the detailed data listings. Also, variations in design and/or operational variables from table to table, photograph to photograph, etc., rather than in individual tables, photographs, etc., are covered by listings of all the related data item location numbers. The user should compare variables from item to item as well as in a single item.

#### **C-8. Coverage**

A total of 24,635 location citations was derived from a total of 2,816 single- or combined-item references (tables, photographs, drawings, figures, text) in the 86 reports (81 publications).

#### **C-9. Project Data Listings**

Listings of available dimensional and other descriptive data pertinent to the project designs investigated in the model tests also are given in Item P5. An example list is given in Table C-3. Entries of "XXXXX" indicate sub-headings; entries of "X" indicate confirmed nonapplicable items; and blanks indicate unavailable information. A definition list for the abbreviations is included in Item P5.



30 Jun 95

Table C-3  
An Example of Project Data File Number (PLEGEND)

00001	PROJECT DATA FILE NUMBER (PLEGEND)	11870	PORT THROAT
00002	DATE 08/14/88	11871	WIDTH
00000	GENERAL INFORMATION	11872	HEIGHT
10100	PROJECT IDENTIFICATION	11873	TOTAL AREA
10110	PROJECT	11874	T. AREA/CULV. AREA
10120	DETAIL	11875	T. WIDTH/CULV. WIDTH
10130	REPORT	11300	TRANSITION CONDUIT
10200	WATERWAY	11310	LENGTH
10210	NAME	11320	SHAPE
10220	MILE	11330	UPSTR SIZE (UXH)
10230	PORT-DOCK NUMBER	11340	DNSTR SIZE (UXH)
10300	PROJECT DIMENSIONS	11350	SLOPE
10310	DESIGN LIFT	11360	BENDS
10320	MAX. LIFT	11370	NOTED ITEMS
10330	MIN. LIFT	11400	OPERATION
10340	USABLE LENGTH	11410	TYPE
10350	CLEAR WIDTH	11420	VALUES USED
10400	PROTOTYPE SYSTEM	11430	VALUE SCHEDULE
10410	INTAKE	11440	INITIAL POOL EL
10420	VALUES	11450	INITIAL CHAMBER EL
10430	FILL/EMPTY	11460	NOTED ITEMS
10440	OUTLET	12000	FILLING VALVE SYSTEM
10450	LOCK GATES	12100	VALUE
10460	EMERG. CLOSURE	12110	TYPE
10500	MODEL STUDY	12120	SIZE (UXH)
10510	TITLE (SHORT)	12130	RADIUS
10520	AUTHOR	12140	TRUNNION EL
10530	LABORATORY	12150	MOIST
10540	UES LIBRARY NO.	12160	VENTS
10550	REPORT DATE	12170	NOTED ITEMS
10560	TEST COMPL. DATE	12200	FLOW PASSAGE
10570	SCALE	12210	SHAPE
10580	SCOPE	12220	SIZE (UXH)
10590	NOTED ITEMS	12230	ROOF EL
11000	INTAKE SYSTEM	12240	INVERT EL
11100	APPROACH	12250	CONTRACTION
11110	CHANNEL TYPE	12260	EXPANSION
11120	CHANNEL LENGTH	12270	WELL
11130	GUIDE-GUARD WALLS	12280	BULKHEAD SLOTS
11140	DEBRIS CONTROL	12290	NOTED ITEMS
11150	VORTEX CONTROL	12300	OPERATION
11160	TRASH RACK	12310	TYPE
11170	NOTED ITEMS	12320	VALUES USED
11200	MANIFOLD	12330	VALUE SCHEDULE
11210	TYPE	12340	INITIAL POOL EL
11220	LOCATION	12350	INITIAL CHAMBER EL
11230	DESIGN SUBMERGENCE	12360	VENTS
11240	PORTS	12370	BULKHEAD SLOTS
11241	NUMBER	12380	NOTED ITEMS
11242	ARRANGEMENT	13000	CULVERT-CHAMBER MANIFOLD
11243	SHAPE	13100	CULVERT
11244	NOTED ITEMS	13110	LENGTH
11250	PORT FACE	13120	SHAPE
11251	WIDTH	13130	SIZE (UXH)
11252	HEIGHT	13140	AREA
11253	TOTAL AREA	13150	TRANSITIONS
11254	T. AREA/CULV. AREA	13160	BENDS
11260	PORT INTAKE	13170	NOTED ITEMS
11261	WIDTH	13200	MANIFOLD
11262	HEIGHT	13210	TYPE
11263	TOTAL AREA	13220	BRANCH LATS, LONGS
11264	T. AREA/CULV. AREA	13230	NUMBER
		13240	ARRANGEMENT
		13250	LENGTH

## Appendix D

### Design of Side-port Systems

#### D-1. Description

A typical sidewall port filling-and-emptying system has a longitudinal culvert in each lock wall extending from the upper pool to the lower pool, with a streamlined intake at the upstream end and a diffusion device at the downstream end. Flow is distributed into and out of the lock chamber by short ports between the longitudinal culverts and the sides of the lock chamber. Two valves are required in each longitudinal culvert, one between the intake and the manifold of lock chamber ports to fill the lock and the other between the manifold of lock chamber ports and the discharge diffuser to release flow in the emptying operation. This discussion is concerned with design of that portion of the system between the filling and emptying valves.

#### D-2. Port Size

From data collected in model tests of an 84-ft-wide lock, three 110-ft-wide locks, and a 150-ft-wide lock, the desirable cross-sectional area for a port is plotted against lock width in Figure D-1. Studies have shown that the extent of the primary zone of diffusion of a submerged jet is a function of jet size and thus the optimum size port is dependent only on lock chamber width. Certainly the degree of surface turbulence in the lock chamber increases as the lift increases and/or as the submergence (difference in elevation between initial lower pool and the lock chamber floor) decreases, but distribution of turbulence across the chamber is independent of lift and submergence. For the 655-ft-long by 84-ft-wide Jonesville Lock, a 6.0-square-foot (sq-ft) port resulted in good distribution of turbulence and ports of other sizes were not tested. In the model study of the 670-ft-long by 110-ft-wide Arkansas River low-lift locks, ports with cross-sectional areas of 6.0, 8.9, 10.4, and 12.7 sq ft were tested. The 6.0-sq-ft ports definitely were too small as the jets from the ports were diffused prior to reaching the opposite side of the lock chamber. This resulted in boils with excess turbulence along the center of the lock chamber and caused large hawser forces on a moored tow. Conditions produced by the 8.9- and 10.4-sq-ft ports were rated as satisfactory. With the 12.7-sq-ft ports longer filling times were required for acceptable hawser forces than with either the 8.9- or 10.4-sq-ft ports. Also turbulence was considered excessive and it was concluded that this port was too large. In model tests for the

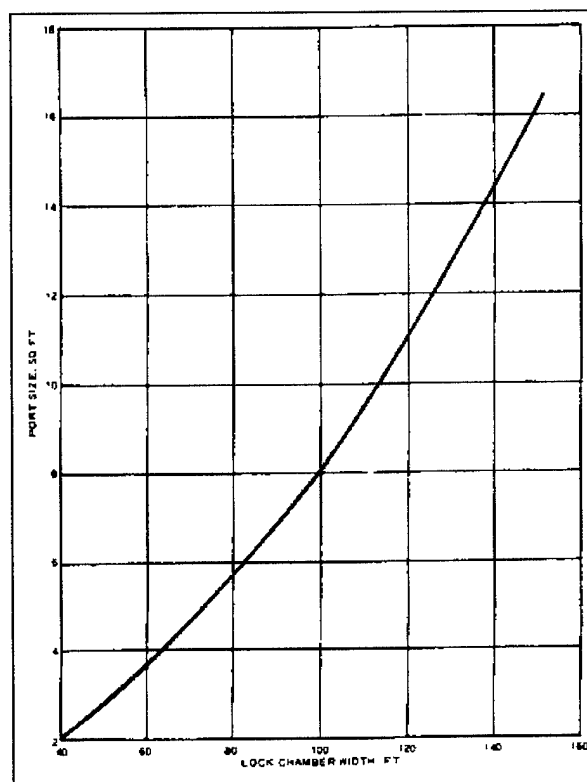


Figure D-1. Recommended port size

1,270-ft-long by 110-ft-wide Cannelton Lock, ports 8.4 and 11.2 sq ft in cross-sectional area were observed. For equal filling times more favorable hawser forces resulted with the 11.2-sq-ft ports. Upon completion of the tests for the Cannelton Lock and the Arkansas River low-lift locks, engineers involved in both studies agreed that the 8.9- and 10.4-sq-ft ports tested in the Arkansas model resulted in more favorable turbulence conditions across the lock chamber than did the 11.2-sq-ft port tested for Cannelton Lock. These engineers are of the opinion that a slightly better design for the filling system for Cannelton Lock could have been developed if a port 9.0 to 10.0 sq ft in cross-sectional area had been used. For the 1,265-ft-long by 110-ft-wide New Cumberland Lock, a port 9.5 sq ft in cross-sectional area was selected. In the model of the 1,290-ft-long by 150-ft-wide Mississippi River-Gulf Outlet Ship Lock, a port 16.2 sq ft in cross-sectional area results in good distribution of turbulence across the lock chamber. Ports of other sizes have not been tested. Obviously a variation in port size of about 5 percent to either side of that recommended is acceptable.

### D-3. Port Spacing

a. Ports in one wall should be staggered with respect to the ports in the other wall so that the jets issuing from one culvert will pass between jets from the other culvert. If ports are spaced too close together, the jets from the opposite walls will meet; and boils will form near the center of the lock, resulting in large hawser forces. If spacing between the ports is too great, the port jets will tend to stray, resulting in some areas of essentially no turbulence and other areas of excess turbulence.

b. Again the areas of excess turbulence will cause large hawser forces. Recommended spacing for the ports in a lock wall is given in Figure D-2. In a 110-ft-wide lock, a spacing of 28 ft center to center for the ports in each wall has been found to be optimum in several model studies. For locks of other widths there are few significant data. In an 84-ft-wide lock, spacings of 22 and 20 ft were tested, and the 20-ft spacing was preferred although a 21.5-ft spacing is indicated in Figure D-2. In a 150-ft-wide lock, only a spacing of 38 ft has been observed and this appears to give satisfactory conditions. Certainly spacing is not so critical that variation of 1 ft on either side of that recommended would result in a noticeable change in conditions.

### D-4. Number of Ports

Following selection of port size and spacing, the next consideration is the number of ports that is feasible for the particular lock. In this connection the port group must be centered with respect to the length of the lock chamber, and it must extend over at least 50 percent of the lock chamber length. If the port group does not extend over at least 50 percent of the chamber length, hawser forces on a tow in either the upstream or downstream half of the lock chamber will be greater than those on a tow that occupies the entire lock chamber. The greater the extent of the port group the better, but usually structural considerations will limit the port group to about 60 percent of the lock chamber length.

### D-5. Culvert Size

After the number of ports that can be accommodated is fixed, then the desirable size for the culverts in the lock walls can be determined. In each culvert the ratio of the total cross-sectional area of the ports to the cross-sectional area of culvert should be about 0.95. If the cross-sectional area of the ports is as large as or larger than the cross-sectional area of the culvert, poor

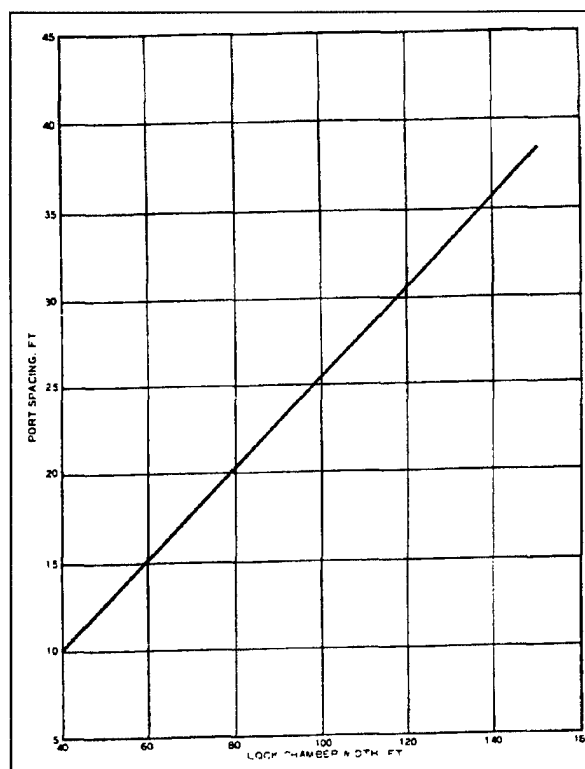


Figure D-2. Recommended port spacing

distribution of flow from the port manifold will result to the extent that during peak discharge of a filling operation, flow is likely to be drawn from the lock chamber by the upstream ports. On the other hand if the port-to-culvert area ratio is too small filling time will be sacrificed without a noticeable improvement in conditions in the lock chamber.

### D-6. Culvert Shape

A culvert square in cross section allows for easy forming of the culvert and port and results in good hydraulic efficiency. However, forming advantages can be maintained with a rectangular cross section and as long as the minimum dimension is at least two thirds of the maximum dimension there will be very little loss in hydraulic efficiency. Frequently wall stability and valve design are simplified by making the height of the culvert greater than the width.

### D-7. Port Shape

There is an advantage in a rectangular port with the width equal to about two thirds of the height. With a

narrow port there is less downstream component in the jet issuing from the port due to the velocity of the flow passing the port in the wall culvert. On the other hand, turbulence in the lock chamber is better distributed with a square port rather than with a long, narrow port. Long, narrow ports result in unstable jets with severe concentrations of turbulence. A port in which the width is about two thirds of the height is as narrow as is feasible without the risk of unstable jets. Also it has been found to be beneficial to flare the sides of the port by as much as, but never more than, 3 degrees. The length of a port should never be less than three times its width and a length of about four times the width is desirable. A port suitable for a 110-ft-wide lock is shown in Figure D-3.

#### **D-8. Port Deflectors**

Even with properly designed ports there is likely to be a downstream component in the jets issuing from the upstream ports in the manifold where velocity of flow past the ports is quite high. Triangular deflectors that tend to counteract this downstream component are beneficial at the upstream one-third of the ports in the manifold. These deflectors reduce the peak upstream hawser force and allow about a 5 percent decrease in permissible filling time. (Permissible filling or emptying time is the time required to fill or empty the lock without causing hawser forces on a rigidly moored tow in a model to exceed the equivalent of 5 tons prototype.) Unfortunately, general rules for design of deflectors for various size ports have not been developed. Satisfactory conditions in a 110-ft-wide lock were obtained with a deflector as shown in Figure D-4. This deflector can be formed by a wall on the lock floor or by a recess in the lock floor. If a recess-type deflector is used, then recesses probably will be desirable at all ports. In this case triangular recesses are suggested for the half of the ports in the upstream end of the lock chamber and rectangular recesses for the ports in the downstream end of the chamber.

#### **D-9. Angled Ports**

There are data from tests in which ports were angled upstream in attempts to gain the same benefits as those gained with deflectors. In all cases conditions resulting with angled ports were not as favorable as those obtained with deflectors.

#### **D-10. Required Submergence**

Submergence is defined in paragraph D-2 as the difference in elevation between the lower pool and the lock

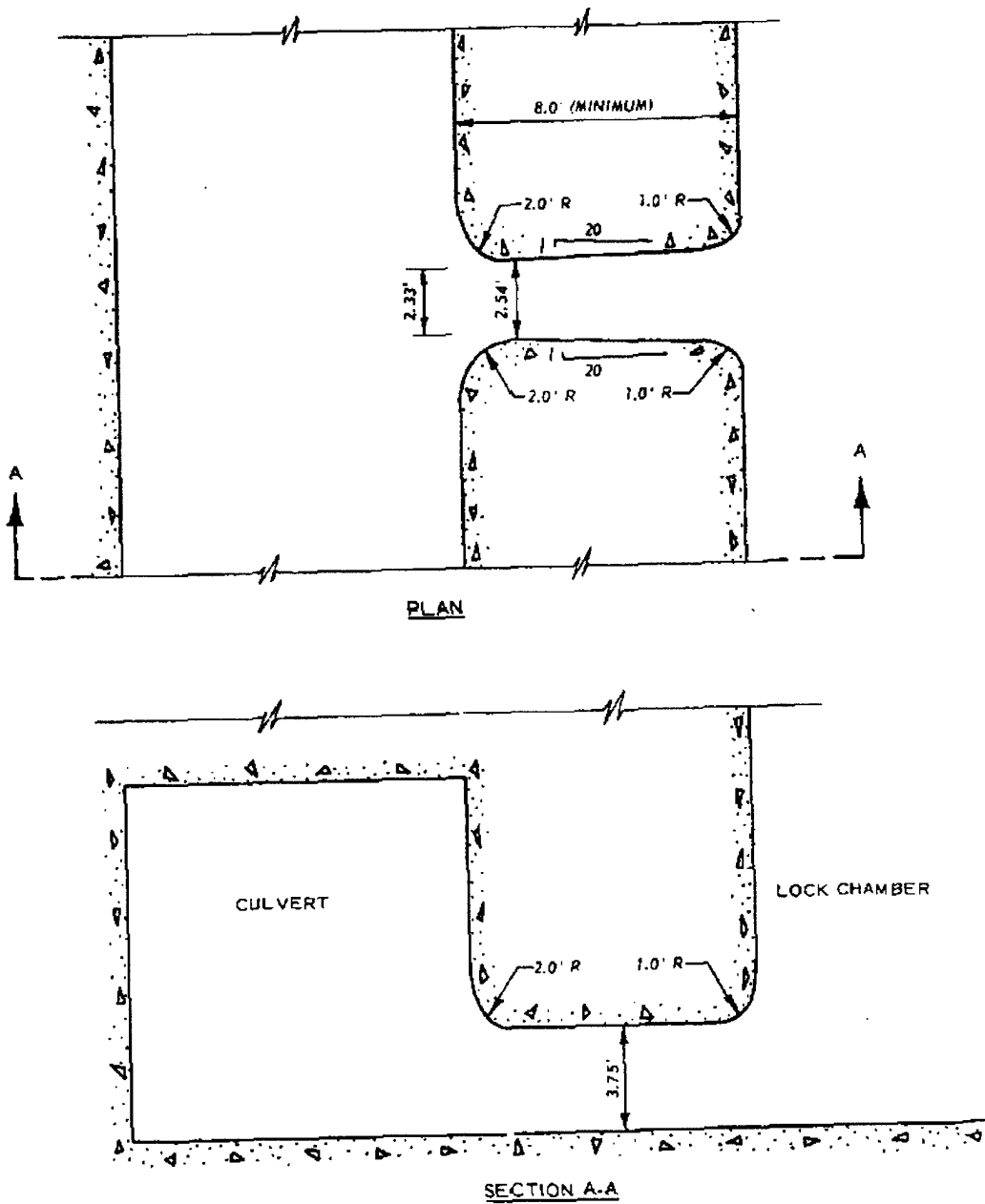
chamber floor. The greater the submergence the faster is the permissible filling time. However, in many cases each foot of submergence provided is quite costly and the designer needs to know the minimum submergence at which satisfactory operation can be expected. Data from various width locks indicate that the jets from the ports expand in an upward direction at the same rate as they expand horizontally. Thus a clear space between the bottom of the vessel using the lock and the floor of the lock chamber equal to one-half of the port spacing is required to prevent direct action of the port jets against the bottom of the vessel. In a 110-ft-wide lock designed for tows of 9-ft draft, a submergence of 23 ft should be provided (9 ft, draft of tow, plus 14 ft clear under tow, one-half of 28-ft port spacing). If a greater submergence than that suggested is provided, then permissible filling times will be shorter; but an increase in clear space under the tow of 100 percent will allow a decrease in permissible filling time of only 10 percent. On the other hand, a decrease in the suggested clear space under the tow of only 20 percent will require a 20 percent increase in permissible filling time.

#### **D-11. Ports Above Chamber Floor**

It may be structurally desirable to have the ports enter the lock chamber at an elevation higher than the lock chamber floor. If this is the case then the ports should be angled down so that the jets are directed at the base of the opposite chamber wall such as was done at the Eisenhower and Snell Locks. Of course the ports never should enter the chamber at an elevation that will result in jets impacting directly on a vessel using the lock.

#### **D-12. Valve Position**

During opening of the filling valves there are depressions in the pressure gradients in the culverts that extend from each valve to a section about 6.5 times the culvert height downstream from the valve. Thus it would be expected that there would be a deficiency in flow from ports placed in this zone. However it is during the valve opening period that the discharge from the upstream ports is likely to be in excess of that desired. In a series of tests for Newburgh Lock it was found that, "with the port manifold placed in positions that resulted in the first two and the first four ports being within the low pressure zone downstream from the valve no differences in filling time or hawser forces could be detected from those obtained with the manifold placed so that all ports were outside of the low pressure zone."



**Figure D-3. Port for 110-ft-wide lock**

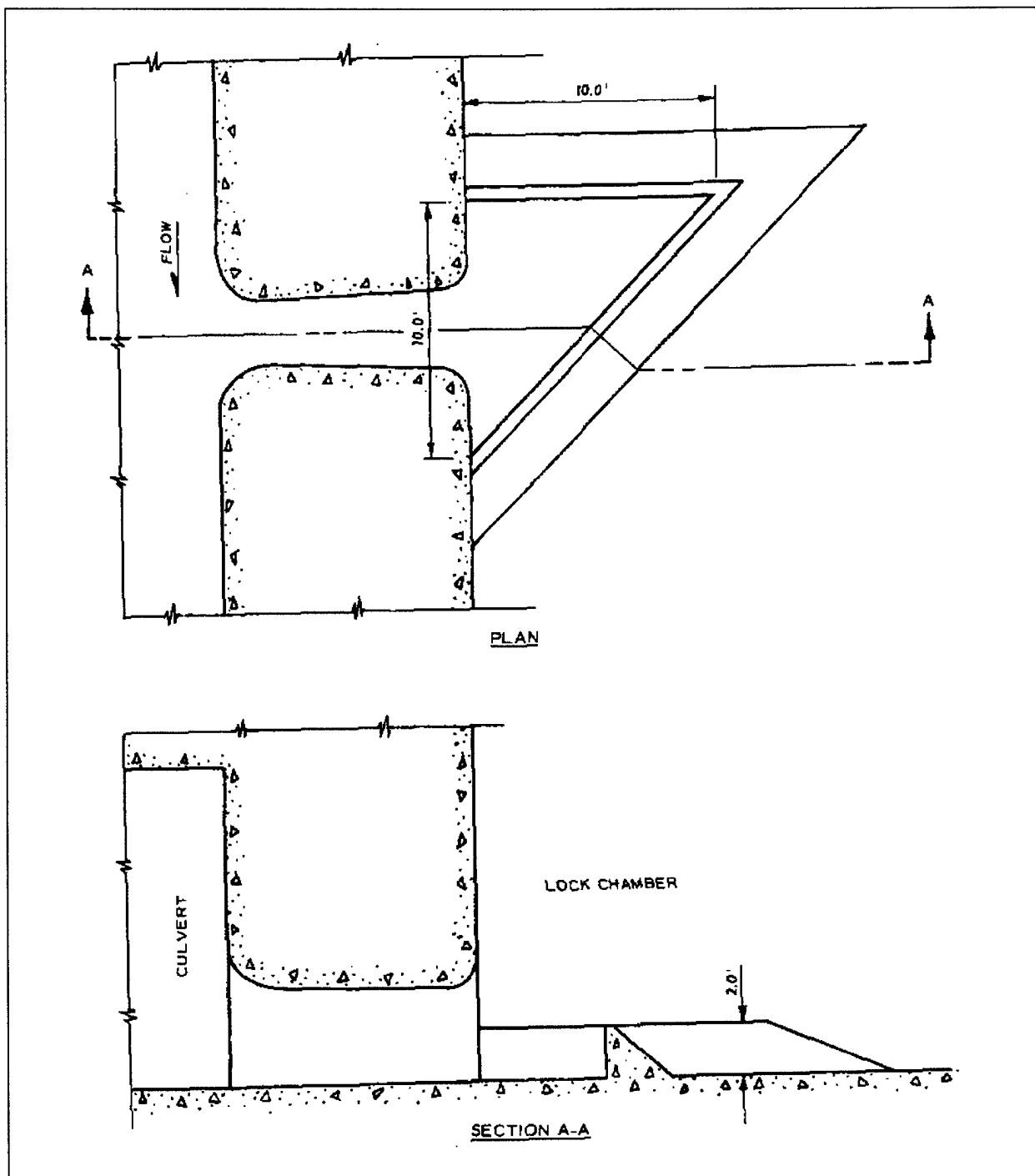


Figure D-4. Port deflector for 110-ft-wide lock

### D-13. Culvert Transitions

If there are transitions in the culverts downstream from the filling valves or upstream from the emptying valves, all ports should be outside of the transition zones as pressures in these zones will be modified even after the valves are fully open. Expansions downstream from the filling valves and contractions upstream from the emptying valves can be used to provide the optimum size culvert through the reach of the port manifold with smaller and thus less costly valves and bulkheads. Of course this will result in greater losses through the contracted reaches of the culvert and somewhat longer filling and emptying times.

### D-14. Suggested Designs

a. A good design for a 670- by 110-ft lock would have 15 ports, as shown in Figure D-3, from each of two 150-sq-ft culverts (minimum dimension at least two-thirds of maximum dimension) and deflectors as shown in Figure D-4 on the five upstream ports in each culvert. If designed for tows of 9-ft draft, minimum lower pool would be 23 ft above the lock chamber floor.

b. Similarly a 1,270- by 110-ft lock would have 28 ports, as shown in Figure D-3, from each of two 280-sq-ft culverts, with deflectors as shown in Figure D-4 on the nine upstream ports in each culvert. Again for tows of 9-ft draft, minimum lower pool would be 23 ft above the lock chamber floor.

c. A 655- by 84-ft lock would require 18 ports, each with a throat area of 6 sq ft, from each of two 115-sq-ft culverts. Deflectors similar to that shown in Figure D-4 would be installed on the six upstream ports in each culvert. If designed for tows of 9-ft draft, minimum lower pool would be 19.5 ft above the lock chamber floor.

### D-15. Valve Times, Filling

a. In Figure D-5 are plotted permissible filling times (hawser forces not in excess of the prototype equivalent of 5 tons in 1:25-scale models) for the designs described in paragraph D-14. In Figure D-6 are plotted the valve times required in the models for the permissible filling times shown in Figure D-5. Also in Figure D-6 are recommended valve times for use in prototype operation. Note that these valve times are essentially the same as were required in the models. It has been established from experience that a prototype lock will fill about 9 percent faster than will its 1:25-scale model but that conditions in the prototype will be satisfactory if the

valves are operated at a rate no faster than was required to limit hawser forces to 5 tons in the model. Thus filling times in the prototype will be about 9 percent faster than those shown in Figure D-5.

b. Valve times required in the model for the 84-ft by 655-ft lock are not shown in Figure D-6 because the culverts used in the tests for the Jonesville Lock were 15 percent smaller than are considered optimum. Actually with the smaller culverts a valve time of about 2 min was satisfactory for all lifts, but with optimum size culverts the valve times recommended in Figure D-6 are considered more appropriate. These valve times were interpolated on the basis of the lock chamber length-to-width ratio. The greater the length-to-width ratio of the lock chamber the greater are the permissible filling times and valve times. For other length-to-width ratios valve times should be interpolated from those shown.

### D-16. Valve Times, Emptying

For emptying, allowable valve times vary with the length-to-width ratio of the lock chamber, as in filling; but unlike in filling, allowable valve times are relatively independent of lift. In a 670- by 110-ft lock a valve time of 2 min is satisfactory for all lifts. A 1,270- by 110-ft lock requires a 4-min valve time for all lifts.

### D-17. Filling and Emptying Computations

a. The usual formula for computing lock filling and emptying times is

$$T - Kt_v = \frac{2 A_L (\sqrt{H + d_f} - \sqrt{d_f})}{2C_L A_c \sqrt{2g}}$$

where

$T$  = filling or emptying time, sec

$K$  = a constant (value depends upon the valve opening pattern, usually about 0.50)

$t_v$  = valve opening time, sec

$A_L$  = area of lock chamber, sq ft

$H$  = lift, ft

$d_p d_e$  = overfill or overempty, ft

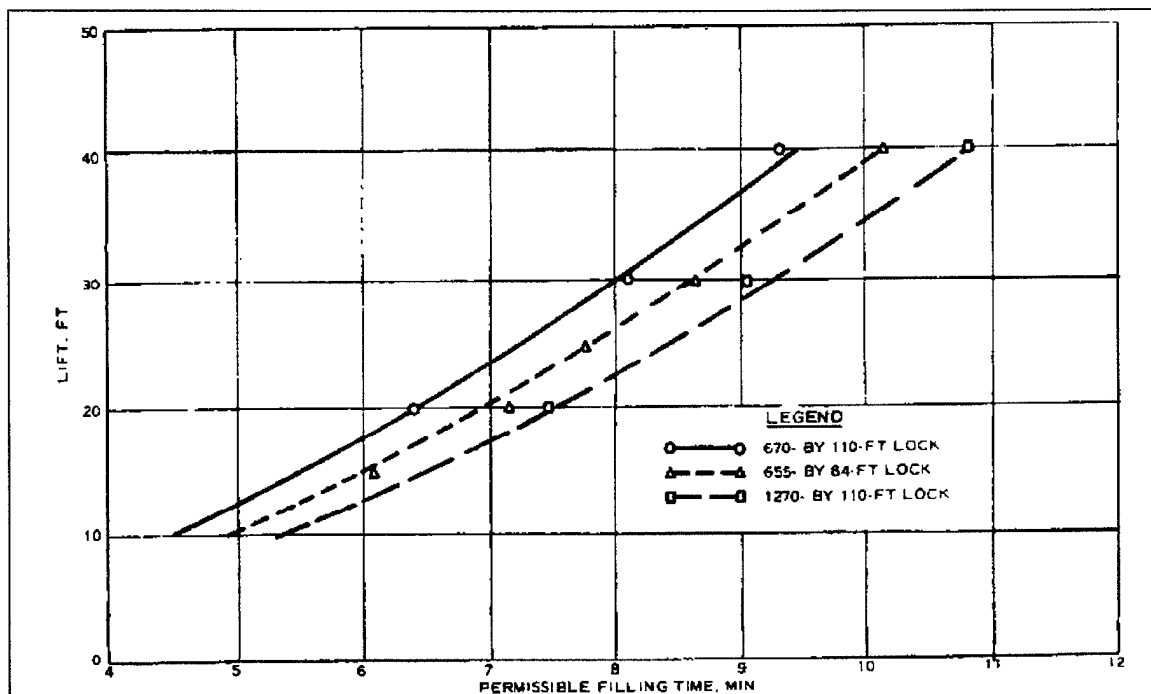


Figure D-5. Permissible filling times--models

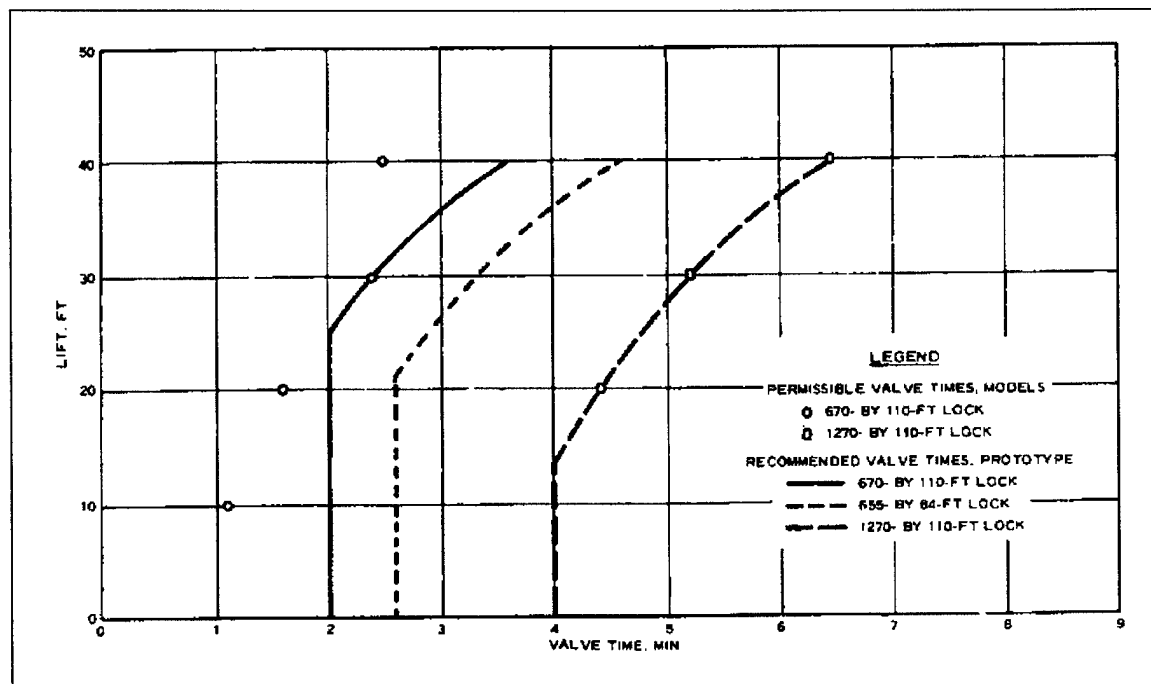


Figure D-6. Valve times--filling



30 Jun 95

$C_L$  = a coefficient (value depends upon losses in system)

$A_c$  = cross-sectional area of culvert, sq ft

$g$  = acceleration of gravity, ft per sec<sup>2</sup>

b. For the systems described in paragraph D-14 with intake and outlet structures essentially as shown in Plate 3-3, values for  $d$  and  $C_L$  are listed in Table D-1.

**Table D-1**  
**Lock Coefficients**

Value	Fill	Empty
$d_p d_o$ , ft	1.00	0.90
$C_L$	0.80	0.72

These values of  $C_L$  are 9 percent greater than those determined in 1:25-scale models.

c. The total head loss through a filling-and-emptying system ( $H$ ) is related to  $C_L$  thus:

$$H = \frac{1}{(C_L)^2} \times v^2/2g \quad (D-1)$$

where

$v$  = velocity in wall culverts through the full open valve, ft per sec

For the systems described in paragraph D-14, the total head loss is distributed as listed in Table D-2.

#### D-18. Discussion

a. The sidewall port filling-and-emptying system is an excellent system for low-lift locks. Although data are

**Table D-2**  
**Distribution of Total Head Loss**

Location	Total Head Loss, $v^2/2g$
Filling	
Upper pool to valve	0.45
Through open valve	0.10
Valve to lock chamber	1.05
Emptying	
Lock chamber to valve	0.93
Through open valve	0.10
Valve to lower pool	0.90

given herein for lifts as great as 40 ft, general use of the system for lifts of more than about 30 ft is not recommended. Improper operation or malfunction of the valves will create conditions that are undesirable at low lifts but become dangerous at lifts of more than about 30 ft.

b. Compared with the bottom longitudinal filling-and-emptying system, which is used for high-lift locks, the sidewall port system has favorable discharge coefficients. However when valve times of 4 min or slower are required for satisfactory operation of the sidewall port system, port system advantages of the more favorable discharge coefficients disappear as the bottom longitudinal system is relatively insensitive to valve speed and a fast valve time can be used at all lifts. Further, permissible filling-and-emptying times can be decreased by enlargement of the culverts in the bottom longitudinal system; this is not the case in the sidewall port system.

## Appendix E

### Design of High-Lift Locks

#### Section I

#### Filling and Emptying System

#### E-1. Objectives

The primary objectives in the design of a lock filling-and-emptying system are rapid fill-and-empty cycle; safety to vessels, structures, and personnel; economic construction; minimum maintenance; and smooth, uninterrupted operation.

#### E-2. Turbulence

The system must be designed so that turbulence and/or surging in the lock chamber does not cause excessive forces on hawser lines used to secure large vessels or create hazards to smaller craft that could be unmoored. Excessive surging could result in forces large enough to break mooring lines, causing damage to the service gates and vessel and endangering operating personnel. Comparison of model tests and prototype observations has shown that when a lock is designed so that certain hawser forces are not exceeded in a model, the prototype will be satisfactory for the moored vessels as well as small craft. These limiting hawser forces as measured in a model are 5 prototype tons (short tons) for barge tows and 10 prototype tons for single vessels (ships) up to

50,000 prototype deadweight tons. Hawser forces for larger vessels are allowed to exceed 10 tons, since they will be required to have more mooring lines than smaller vessels.

#### E-3. Flow

For high lifts, the flow into the lock chamber must be equally distributed if objectionable turbulence and hawser stresses are to be avoided while accomplishing acceptable filling times. Through a series of model tests of specific projects (Table E-1) and general studies, a balanced flow system has been developed for various locks. This system eliminates the surge and oscillation inherent in the sidewall port culvert and end filling systems by distributing flow uniformly throughout the lock chamber. During filling of the lock when the filling valves are open and the emptying valves are closed, flow enters culverts in each sidewall through intakes in the upper pool and is carried to the midpoint of the lock chamber where it is equally divided and directed to the upstream and downstream ends of the chamber. Flow in each end of the lock chamber is then divided into distribution culverts and discharged through a manifold of small ports into the lock chamber. During emptying of the lock when the emptying valves are open and the filling valves are closed, water from the lock chamber enters the distribution culverts through these small ports and is carried to the midpoints of the lock chamber where it is equally divided into the sidewall culverts and discharged into the lower pool.

**Table E-1**  
**Specific Locks With Balanced Flow Filling-and-Emptying System**

Name	Location	Lift	Lock Chamber Size
Bankhead	Warrior River, AL	69 ft 21 m	110 ft x 670 ft 33.5 m x 240.2 m
Bay Springs	Tennessee-Tombigbee Waterway, MS	86 ft 26.2 m	110 ft x 670 ft 33.5 m x 204.2 m
Lower Granite	Snake River, WA	105 ft 32 m	86 ft x 675 ft 26.2 m x 205.7 m
Trinity River (proposed)	Trinity River, TX	60 ft 18.3 m	84 ft x 655 ft 25.6 m x 199.6 m
Walter Bouldin (proposed)	Coosa River, AL	130 ft 39.6 m	84 ft x 630 ft 25.6 m x 192 m

*Section II*  
*Crossover Culverts*

#### **E-4. Methods**

The portion of the system near the midpoint of the lock where flow from each wall culvert is divided and directed to the ends of the chamber is designated the crossover culverts. Two methods of dividing flow have been used:

- (a) The side-by-side culvert method where flow is divided by a vertical wall (Figure E-1).
- (b) The over-and-under culvert method where flow is divided by a horizontal splitter (Figure E-2).

The over-and-under crossover culvert (horizontal flow divider) is preferred because it provides a more stable distribution of flow and is less likely to result in cavitation. Also, this method is more hydraulically efficient than the side-by-side method. In fact, the only reason for using the side-by-side method would be the cost advantage that may result under certain foundation conditions because the over-and-under crossover requires more depth to construct.

#### **E-5. Divider Piers**

The divider pier is an important feature of the side-by-side crossover culvert because it provides a means for directing 50 percent of the flow to each end of the lock chamber and results in more stable flow conditions through the crossover culverts. However, this area is subject to cavitation that can occur in cores of vortices shed from the divider piers with high lifts. Therefore, this method of division is not recommended with lifts greater than 60 ft (18.3 meters (m)).

#### **E-6. Combining Culverts**

With either crossover culvert system, flows from the two wall culverts discharge into a common culvert in each half of the lock so that the entire distribution system will be used even though only one wall culvert is in operation. These are called combining culverts. A relatively constant cross-sectional area is maintained from the wall culvert through the crossover and combining culverts. With the over-and-under crossover culvert system, combining of flow is accomplished as shown in Figure E-2, and with the side-by-side crossover culvert, combining of flow is accomplished as shown in Figure E-1. With the latter system, distribution of flow in the combining

culvert with only one wall culvert operating is very sensitive to the location of the downstream edge of the separation pier. If the downstream edge of the pier is too short, excessive flow passes to the side of the combining culvert opposite the active culvert; if too long, excessive flow remains on the side of the combining culvert adjacent to the active culvert.

#### **E-7. Distribution Culverts**

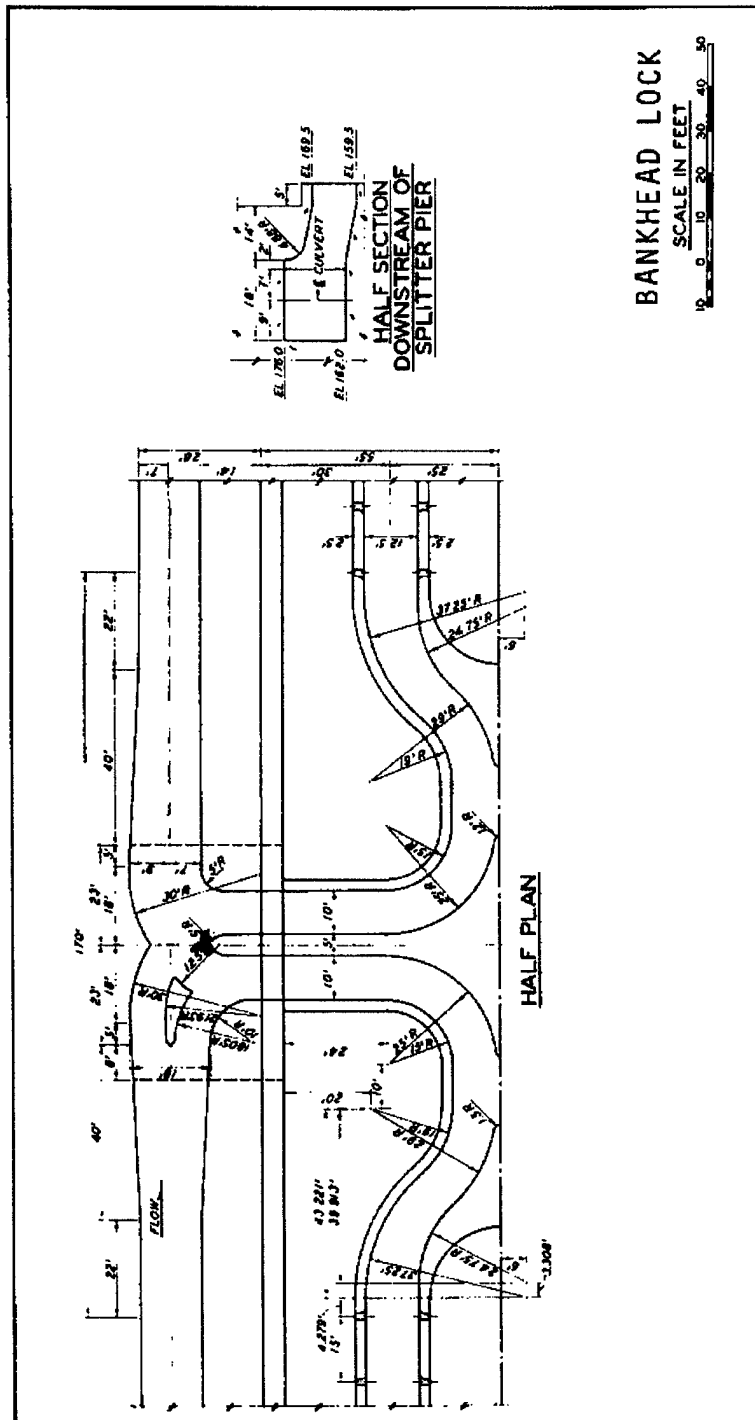
From the combining culvert, flow is redivided into two or four distribution culverts in each end of the lock as shown in Figures E-1 and E-2. The exact conditions under which two or four distribution culverts are needed have not been clearly established, but this depends upon lift, culvert size, and lock chamber length-to-width ratio. In the Bankhead Lock and Bay Springs Lock, two distribution culverts in each half of the chamber were adequate. In a series of general tests with a 110- by 1,270-ft (33.5- by 387.1-m) lock, four distribution culverts were required. Thus, with a length-to-width ratio of 6.1, two distribution culverts were adequate, but with a length-to-width ratio of 11.5, four distribution culverts were required. In the Lower Granite Lock, with a length-to-width ratio of 7.9, four distribution culverts were used. For locks proposed on the Trinity River, length-to-width ratio of 7.8, model tests showed that two distribution culverts were adequate, but the maximum lift was only 60 ft (18.3 m). In the proposed Walter Bouldin Lock with a lift of 130 ft (39.6 m) and a length-to-width ratio of 7.5, two distribution culverts produced satisfactory hydraulic conditions in model tests.

#### **E-8. Cross-Sectional Area**

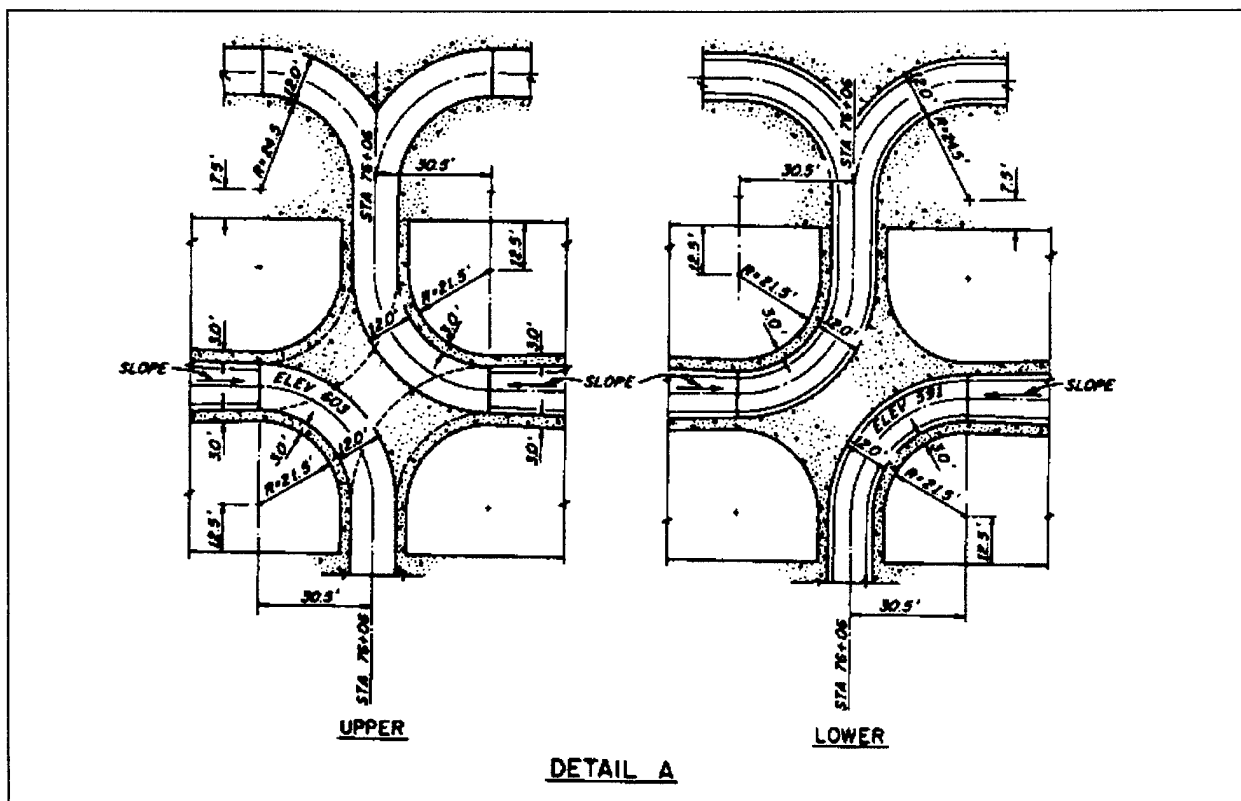
Certainly, the four distribution culverts result in a more symmetrical flow pattern in the chamber than do two culverts, but it also is a more costly system with increased hydraulic losses. Regardless of whether two or four distribution culverts are used in each end of the chamber, it is desirable for the combined cross-sectional area of these culverts to be greater than the cross-sectional area of the wall culverts. This not only has a favorable influence on filling and emptying times, but also reduces bursting pressures during filling and collapsing pressures during emptying in the crossover and combining culverts.

#### **E-9. Port Manifolds**

In each of the distribution culverts a manifold of ports discharges flow into the lock chamber. These ports extend over at least 50 percent of the length of the



**Figure E-1. Balanced flow filling and emptying. Side-by-side crossover culverts with two distribution culverts in end of lock**



**Figure E-2. Balanced flow filling and emptying. Over-and-under crossover culverts with two distribution culverts in each end of lock**

chamber. In designs with four distribution culverts (one pair in each end) the port manifolds are centered on the one- and three-quarter points of the chamber, and each manifold extends over at least 12.5 percent of the total length of the lock. The size of the ports ranges from 4.20 to 6.28 ft<sup>2</sup> (0.39 to 0.58 square meters (m<sup>2</sup>)). A port area to distribution culvert area ratio of approximately 1.0 results in good distribution of flow in the lock chamber. Port spacings of 14 to 18 ft (4.27 to 5.49 m) were used in the various designs discussed earlier and spacing appeared to have very little effect on flow conditions. The prime objective in port spacing is to use as much available length of the lock chamber as possible.

#### E-10. Baffles

A large portion of the energy of the jets issuing from the ports is dissipated in turbulence in trenches along the

distribution culverts. Baffles on the walls of the trenches are used to prevent upwelling of the jets from the ports.

#### E-11. Bottom Filling and Emptying

The bottom longitudinal filling-and-emptying system unquestionably is the best system developed to date for high-lift locks in the United States. The locks that have been built using this system have operated very efficiently with very little turbulence in the lock chamber. For example, the Lower Granite Lock fills in about 8.1 min with a lift of 105 ft (32 m) and the Bankhead Lock fills in 7.7 min with a 69-ft (21-m) lift. The water surface in both of these locks is extremely smooth during the entire filling cycle. Model tests indicate that the Bay Springs Lock will fill in about 8.3 min with a lift of 86 ft (26.2 m).

*Section III*  
*Filling-and-Emptying*  
*Culvert Gate Valves*

## **E-12. Reverse Tainter Gates**

The filling-and-emptying culvert valves of high-lift locks are very important in the overall design of the system. Reverse tainter gates have been used as the control valves in all high-lift locks recently constructed in the United States. When a large volume of air is drawn into the culverts, the air may pass through the ports and erupt in the lock chamber. The resulting disturbances would be hazardous. By reversing the tainter gates, that is, placing the trunnions upstream from the skin plate and sealing against the downstream end of the valve well, air is prevented from entering the culvert at the valve recess during the opening period if the pressure gradient drops below the top of the culvert.

## **E-13. Tainter Valves**

Three structurally different types of reverse tainter valves (horizontally framed, double skin plate, and vertically framed) have been used in the United States. The horizontally framed valve is desirable structurally, but the double skin plate and vertically framed are less susceptible to critical hydraulic loads and load variations during the opening cycle.

## **E-14. Cavitation**

Prevention of cavitation downstream from the valves is a very difficult problem for designers, particularly as lifts increase to values greater than 100 ft (30.5 m). High velocities and low pressures are induced as flow accelerates immediately downstream from the valves during the valve opening period. In some instances, the local flow acceleration is sufficient to lower the local pressure to the vapor pressure of water and form cavities within the flow. These cavities collapse rapidly or implode either in the water or against the downstream boundaries as they enter the increased pressure that results from the decreased velocity of flow as it expands and decelerates in the culvert downstream of the valve. This has resulted in lockmasters reporting loud pounding noises indicating cavitation implosions within the flow. In some instances, these booms have been violent enough to shake the lock walls and break windows. The implosion of the cavities against solid boundaries results in rapid pitting or damage to valves and appurtenances and to the concrete culverts.

## **E-15. Pressures**

In some designs, pressures low enough to cause cavitation are avoided by submerging the culvert at the location of the valve so that the pressure gradient is maintained above the top of the culvert. However, as lifts increase, it becomes increasingly costly to provide adequate submergence. Through prototype tests at some of the high-lift locks on the Columbia River it was found that admitting a *controlled* amount of air into the culverts at each valve virtually eliminated the pounding noises. Air was drawn through a vent placed downstream from the valve into the culvert system during the valve opening period, was entrained as small bubbles in the highly turbulent flow, and emerged in the lock chamber so entrained that it merely caused the water to look milky. It was concluded that the air cushioned the collapse of the large cavities, eliminated shock pressures, and thus eliminated the pounding noises. This procedure allowed the culverts to be placed at a much higher elevation, thus minimizing excavation costs. Several locks have been constructed in the United States using this procedure, and no operation difficulties or hazardous conditions have been reported where pressures on the culvert roof were low enough to draw air during the valve opening period.

## **E-16. Culvert Expansions**

a. Through model tests it was found that expanding the culvert roof upward downstream from the valve (Figure E-3) would increase pressures on the roof of the culvert just downstream from the valve. Also, in these tests it was found that the location of the expansion with respect to the valve directly affected the pressure on the roof of the culvert in the area immediately downstream from the valve. Thus, the use of expansions downstream from the culvert valves is a very practical means of controlling the pressures and allowing the valves to be set at a more economical elevation.

b. Expansions started at locations immediately downstream from the valve to a distance of 6.5 times the valve height (Figure E-3). Valve energy loss coefficients are essentially the same with no roof expansion, and with roof expansions beginning 4 and 6.5 times the valve height downstream from the valve. Thus, culvert expansions that begin 4 valve heights or more downstream have no effect on the loss coefficient for valve openings of 30 percent or greater. Expansions beginning within a distance of 4 valve heights of the valve increased energy loss coefficients as the expansion was placed closer to the valve.

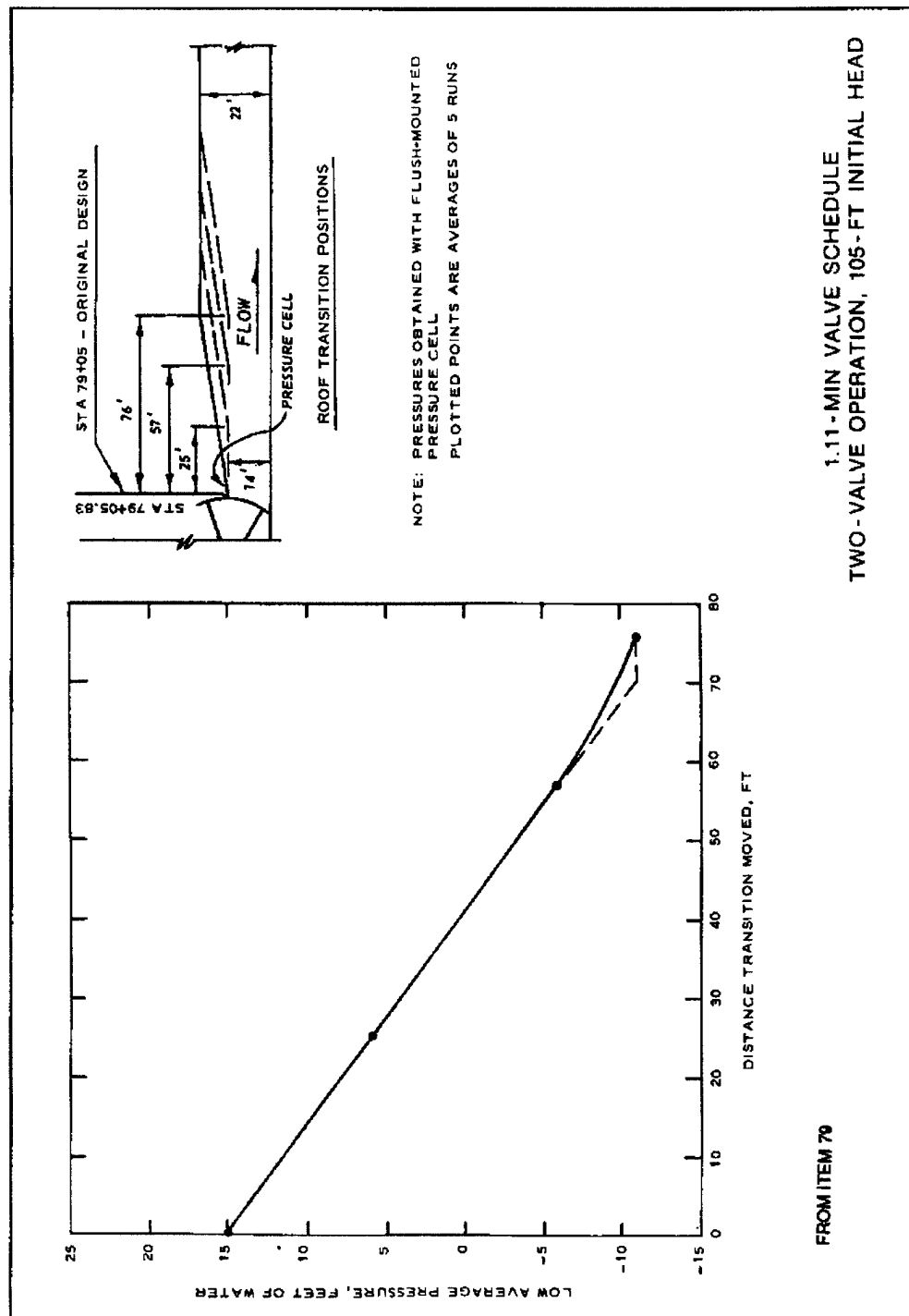


Figure E-3. Effect of culvert expansions on valve pressure drop

## Appendix F Computer Runs

### Section I. H5310

#### EXAMPLE of Lock Filling

CONDUIT GEOMETRY: LENGTH = 490.0 FT. WIDTH= 14.0 FT.  
HEIGHT= 14.0 FT. N= 2-CULVERT OPERATION)

CHAMBER GEOMETRY: LENGTH = 670.0 FT. WIDTH =110.0 FT.

LOSS COEFFICIENT: INTAKE .200  
UPSTREAM CONDUIT .050  
DOWNSTREAM CONDUIT .950  
MANIFOLD .750  
TOTAL (VALVE OPEN) 2.050 LOCK COEF. = .698

ELEVATIONS: UPPER POOL 409.60  
LOWER POOL 329.90  
CULVERT ROOF 312.00

VALVE OPENS AT 1.00-MIN. RATE FOR 1.00 MINUTES

ACC. VEL. ERROR TO I= 47 IS .06014  
ACC. VEL. ERROR TO I= 54 IS .33680

LOCK FILLS TO UPPER POOL IN 9.37 MINUTES  
EXTREME ELEVATION AT TIME = 10.60 MINUTES  
MAX COMPUTED OVERTRAVEL = 1.27 FT.

VALVE PARAMETERS				ELEVATIONS (FT-DATUM)				
TIME OPEN (N)	CONT. RATIO	LOSS COEF.	TOTAL INFLOW	LOCK CHAMBER	US VALVE WELL	PIEZ. HD VALVE	DS VALVE WELL	CAV. PAR.
.00	1.00	.80	10000.00	0.	329.90	409.60	329.90	9.99
.20	.13	.77	86.65	2802.	330.13	408.41	328.93	.78
.40	.29	.66	19.28	5598.	330.81	405.64	320.13	.59
.60	.49	.67	4.42	9865.	332.07	397.31	314.73	.49
.80	.73	.76	.73	15220.	334.11	380.34	327.05	.71
1.00	1.00	.90	.10	18095.	336.83	368.24	360.48	2.03
2.00	1.00	.90	.10	16954.	351.33	373.29	366.48	2.48
3.00	1.00	.90	.10	14989.	364.33	381.22	375.90	3.51
4.00	1.00	.90	.10	13024.	375.73	388.17	384.15	5.04
5.00	1.00	.90	.10	11059.	385.34	394.15	391.25	7.45
6.00	1.00	.90	.10	9094.	393.74	399.15	397.19	9.99
7.00	1.00	.90	.10	7129.	400.34	403.18	401.98	9.99
8.00	1.00	.90	.10	5164.	405.35	406.23	405.60	9.99
9.00	1.00	.90	.10	3199.	408.75	408.31	408.06	9.99
10.00	1.00	.90	.10	1234.	410.56	409.41	409.37	9.99
11.00	1.00	.90	.10	-658.	410.77	409.57	409.52	9.99
12.00	1.00	.90	.10	-1257.	409.87	409.48	409.32	9.99

RATE		VEL HDS(F)		DIFFERENTIAL HDS(F)			
RISE (F/M)	VEL. (F/S)	REF. AREA	VENA CONT.	VALVE	TOTAL	INERTIA	OVERALL
.00	.000	.000	.000	.000	79.700	79.700	.000
.20	2.281	7.147	.793	80.472	68.724	70.270	9.055
.40	4.558	14.282	3.167	88.676	61.076	67.252	11.425
.60	8.031	25.166	9.835	92.407	43.447	62.624	15.564
.80	12.394	38.828	23.410	76.693	17.183	42.832	13.311
1.00	14.731	46.160	33.086	40.847	3.309	47.827	5.078
2.00	15.802	43.249	29.045	35.856	2.905	59.543	-1.269
3.00	12.703	38.238	22.704	28.029	2.270	46.542	-1.271
4.00	10.603	33.225	17.141	21.162	1.714	35.139	-1.271
5.00	9.003	28.212	12.359	15.258	1.236	25.336	-1.271
6.00	7.404	23.199	8.357	10.318	.836	17.133	-1.271
7.00	5.804	18.187	5.136	6.341	.514	10.529	-1.271
8.00	4.204	13.174	2.695	3.327	.269	5.525	-1.271
9.00	2.605	8.161	1.034	1.277	.103	2.120	-1.271
10.00	1.005	3.149	.154	.190	.015	.316	-1.271
11.00	-.535	-1.678	.044	.044	.004	.090	-.971
12.00	-1.023	-3.207	.160	.160	.016	.327	2.060

DO YOU NEED TO STORE THE OUTPUT IN A DATA FILE? Y OR N

ENTER END OR RERUN

E

Stop - Program terminated.



30 Jun 95

## Section II. H5320

## EXAMPLE Downstream Surge

OUTPUT CODES: AP= 1 AQ= 1 AR= 1 AS= 1

## AP. PROBLEM STATEMENT

1. TRAPEZOIDAL CANAL: INITIAL DEPTH= 12.90 FT INITIAL FLOW= .00 CFS  
BOTTOM WIDTH= 220.00 SIDESLOPE: 1V: 1.000H
2. INITIAL STATION= 731.00 FT  
STATION VALUES INCREASE DOWNSTREAM
3. INITIAL TIME= .0 SEC  
TIME STEP= 10.0 SEC  
TOTAL STEPS= 24
4. LOCK EMPTYING: SURGE TRAVELS DOWNSTREAM.  
LOCK-CHAMBER EQUALIZATION TIME= 660.0 SEC
5. LOCK FLOW PLUS INITIAL CHANNEL FLOW:

TIME (SEC)	FLOW (CFS)	TIME (SEC)	FLOW (CFS)	TIME (SEC)	FLOW (CFS)
.0	.000	80.0	15950.000	160.0	13750.000
10.0	2750.000	90.0	15675.000	170.0	13475.000
20.0	5500.000	100.0	15400.000	180.0	13200.000
30.0	8250.000	110.0	15125.000	190.0	12925.000
40.0	11000.000	120.0	14850.000	200.0	12650.000
50.0	13750.000	130.0	14575.000	210.0	12375.000
60.0	16500.000	140.0	14300.000	220.0	12100.000
70.0	16225.000	150.0	14025.000	230.0	11825.000

## 6. PROFILES NEEDED AT THE FOLLOWING 1 TIMES (SEC):

120.000

## 7. HYDROGRAPHS NEEDED AT THE FOLLOWING 1 STATIONS (FT):

731.000

## AQ. SURGE CHARACTERISTICS:

STEP	TIME (SEC)	FLOW (CFS)	SURGE VEL. (FPS)	DEPTH (FT)	AVE. FROUDE VEL. NUMBER
1	.000	.000	19.839	12.900	.000
2	10.000	2750.000	20.458	13.444	.043
3	20.000	5500.000	21.701	13.958	.082
4	30.000	8250.000	22.858	14.445	.117
5	40.000	11000.000	23.942	14.911	.149
6	50.000	13750.000	24.964	15.357	.178
7	60.000	16500.000	25.932	15.787	.204
8	70.000	16225.000	26.392	15.745	.202
9	80.000	15950.000	26.299	15.702	.199
10	90.000	15675.000	26.206	15.660	.197
11	100.000	15400.000	26.113	15.617	.194
12	110.000	15125.000	26.019	15.574	.191
13	120.000	14850.000	25.924	15.531	.189
14	130.000	14575.000	25.829	15.487	.186
15	140.000	14300.000	25.734	15.444	.183
16	150.000	14025.000	25.638	15.400	.180
17	160.000	13750.000	25.542	15.356	.178
18	170.000	13475.000	25.445	15.312	.175
19	180.000	13200.000	25.347	15.268	.172
20	190.000	12925.000	25.250	15.224	.169
21	200.000	12650.000	25.151	15.179	.166
22	210.000	12375.000	25.052	15.135	.163
23	220.000	12100.000	24.953	15.090	.160
24	230.000	11825.000	24.853	15.045	.150

EXAMPLE Surge Upstream

OUTPUT CODES: AP= 1 AQ= 1 AR= 1 AS= 1

AP.PROBLEM STATEMENT

1. TRAPEZOIDAL CANAL: INITIAL DEPTH= 15.50 FT INITIAL FLOW= .00 CFS  
BOTTOM WIDTH= 220.00 SIDESLOPE= 1V: 1.000H
2. INITIAL STATION= 1400.00 FT  
STATION VALUES INCREASE UPSTREAM
3. INITIAL TIME= .0 SEC  
TIME STEP= 10.0 SEC  
TOTAL STEPS= 24
4. LOCK FILLING: SURGE TRAVELS UPSTREAM.  
LOCK-CHAMBER EQUALIZATION TIME= 480.0 SEC
5. LOCK FLOW PLUS INITIAL CHANNEL FLOW:

TIME (SEC)	FLOW (CFS)	TIME (SEC)	FLOW (CFS)	TIME (SEC)	FLOW (CFS)
0	.000	80.0	16190.480	160.0	12952.380
10.0	2833.333	90.0	15785.710	170.0	12547.620
20.0	5666.667	100.0	15380.950	180.0	12142.860
30.0	8500.000	110.0	14976.190	190.0	11738.100
40.0	11333.330	120.0	14571.430	200.0	11333.330
50.0	14166.670	130.0	14166.670	210.0	10928.570
60.0	17000.000	140.0	13761.900	220.0	10523.810
70.0	16595.240	150.0	13357.140	230.0	10119.050

6. PROFILES NEEDED AT THE FOLLOWING 1 TIMES (SEC):

120.000

7. HYDROGRAPHS NEEDED AT THE FOLLOWING 1 STATIONS (FT):

1400.000

AQ.SURGE CHARACTERISTICS:

STEP	TIME (SEC)	FLOW (CFS)	SURGE VEL. (FPS)	DEPTH (FT)	AVE. FROUDE VEL. NUMBER (FPS)
1	.000	.000	-21.640	15.500	.000 .000
2	10.000	2833.333	-21.086	14.962	.804 .038
3	20.000	5666.667	-19.857	14.391	1.672 .080
4	30.000	8500.000	-18.521	13.779	2.619 .128
5	40.000	11333.330	-17.050	13.113	3.670 .184
6	50.000	14166.670	-15.398	12.376	4.861 .251
7	60.000	17000.000	-13.488	11.533	6.259 .335
8	70.000	16595.240	-12.564	11.661	6.043 .322
9	80.000	16190.480	-12.879	11.787	5.833 .309
10	90.000	15785.710	-13.185	11.909	5.629 .297
11	100.000	15380.950	-13.482	12.028	5.430 .285
12	110.000	14976.190	-13.772	12.145	5.236 .273
13	120.000	14571.430	-14.055	12.260	5.047 .262
14	130.000	14166.670	-14.331	12.372	4.862 .251
15	140.000	13761.900	-14.601	12.483	4.681 .241
16	150.000	13357.140	-14.864	12.591	4.505 .231
17	160.000	12952.380	-15.123	12.698	4.332 .221
18	170.000	12547.620	-15.376	12.802	4.162 .212
19	180.000	12142.860	-15.623	12.905	3.995 .202
20	190.000	11738.100	-15.867	13.007	3.832 .193
21	200.000	11333.330	-16.105	13.107	3.672 .185
22	210.000	10928.570	-16.340	13.206	3.514 .176
23	220.000	10523.810	-16.570	13.303	3.359 .168
24	230.000	10119.050	-16.796	13.399	3.207 .159

## Appendix G Mechanical Lifts

### G-1. General

In Germany, France, and Belgium, structures have been built to transfer vessels from one water level to another without using navigation locks. These structures are known as mechanical lifts and move a vessel either vertically upward and downward or upward or downward on an inclined plane. In the early part of the 19th century there were two or three such devices in the United States. However, these "lifts" were quite small and involved moving a small canal boat up an inclined track on a wheeled truck arrangement.

### G-2. Types

a. Ship elevators or vertical mechanical lifts have been built in Germany to serve in place of locks where lockage water was not available. One of the first ones was built on the Dortmund-Ems Canal at Henrichenburg in 1899. This mechanical lift was used until 1962 and was then replaced with a new one. It consists of a rectangular tank with a gate in each end. This rectangular tank is supported on two air-filled flotation chambers that move up and down in water-filled shafts underneath the structure. The flotation chambers provide enough buoyancy to balance the weight of the water-filled tank. When the rectangular tank (trough) is at the lower canal level, it connects directly to the end of the canal. The gate in the trough is lowered, the gate in the end of the canal is lowered, and a vessel waiting in the canal enters the trough. When the vessel is moored in the trough, the gates in the ends of the canal and the trough are closed. The trough is raised to the upper canal level by means of motor-driven threaded vertical shafts running through nuts attached to each corner of the trough. Rotation of the shafts are synchronized, and the trough remains level at all times. Since the flotation chambers provide an upward force equal to the weight of the tank, the threaded shafts have only to overcome mechanical friction and control movement of the tank. When the trough is secured to the end of the upper canal, the gates in the ends of the trough and the canal are opened, and the vessel can depart. Transfer of a vessel from the upper canal to the lower canal is accomplished in a similar fashion. The trough is 295 ft long, 39 ft wide, and 10 ft deep, and can transit a 1,500-ton (2,200-pound ton) vessel in about 30 min. The difference in elevation is about 46 ft.

b. Inclined plane mechanical lifts of two different designs have been built in Belgium and France. In the French project a water-filled tank or trough moves sideways up and down on rails on an inclined plane. The action is similar to the Henrichenburg lift, except the trough moves up an incline instead of vertically, and the dead weight of the trough (plus water) is offset by counterweights moving in trenches on the incline. The French project is located on the Rhine-Marne Canal near Arzwiller, France. The trough moves through a vertical distance of 44 m (144 ft) over a horizontal length of about 100 m (328 ft). It is designed for 300-ton vessels (2,200-pound tons) and replaces 17 very old, small canal locks.

c. The Belgian inclined plane lift is located in the Brussels-Charleroi Canal. There are two separate parallel tracks at this lift, and the troughs move up endways. The horizontal length of the incline tracks is 4,700 ft, and the vertical distance of the incline is about 220 ft. The travel time for the trough is 20 min. Allowing for a total entry and start-up time of 5 to 10 min and a stopping and exit time of 5 to 10 min, the total transit time would be about 35 to 40 min. The two troughs operate independently and have dimensions of 285 by 39 by 10 ft. Each trough can carry one 1,350-ton (2,200-pound ton) vessel, which has almost the same carrying capacity as a 1,500 ton (2,000-pound ton) barge in the United States.

### G-3. Capacity

If three conventional 110- by 600-ft locks were used to overcome the 220-ft difference in elevation, each lock would have a lift of about 73 ft. The transit time for an eight-barge tow through each of these locks would be about 25 min. Adding 15 min for travel time between locks (assuming the locks are 2,500 ft apart) gives a total travel time of 90 min (1.5 hr) to transit 12,000 short tons. To transit 12,000 tons through the incline (moving in the same direction) would require four trips for each two troughs, which would total 5.33 hr ( $8 \times 40$  min). Thus, the net total transit time required to move 12,000 tons through the incline is 3.5 times greater than the time required to move 12,000 tons through three locks and travel a distance of about 5,000 ft. Moreover, the lock system would have more than 3.5 times the capacity of the incline, because all three of the locks would not be in use by one tow at the same time.

#### G-4. Water Slopes

a. French entrepreneurs have developed and patented a system wherein a wedge-shaped volume of water is pushed up or down a sloping rectangular channel with a vessel floating in a wedge of water. A "water slope" (Figure G-1) is located at Mon Tec, France. The rectangular channel is 20 ft wide, is on a 3 percent slope, and will accommodate a 300-ton vessel with a 7-ft draft. The entire structure replaces five old locks.

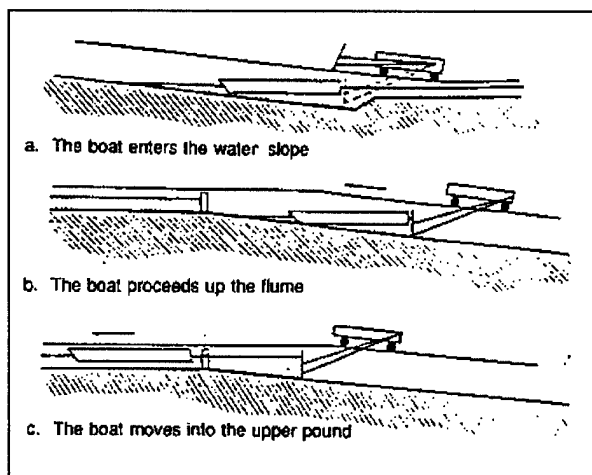


Figure G-1. Water slope

b. The system apparently performs very well in the present situation, but to be commercially feasible in the United States the channel would have to be 4 to 5 times wider, the walls would have to be several times higher in order to provide adequate depth for a 580-ft tow, and structural design problems would be extremely complex for the greater sizes. The system could not possibly be energy efficient.

#### G-5. Separate Facilities for Recreational Craft

a. At places where recreational craft appear in considerable quantities, the introduction of separate handling facilities may be worthwhile. Ten of these have been noted in paragraph 7-32. This is particularly true when the period of peak recreational demand corresponds to the period of peak commodity movement. Such separate facilities could be canvas slings or steel tanks to lift the craft from one level to another, separate small locks out of the main navigation channel, or an inclined plane moving lock such as has been used in Europe and in the

early canal development in the United States. Separation of recreational traffic from towboat traffic would also appear to be a safety improvement.

b. Analyses of alternative small craft lifts were considered at Kentucky Lock and indicated that the inclined-plane type would be more feasible from the standpoint of economics and operation. The inclined plane would be laid out on a steel superstructure that would carry the tracks on a uniform grade up the downstream side of the embankment to an elevation permitting adequate clearance over the railroad and highway. The superstructure would then convey the tracks across the top of the dam to a similar inclined plane on the upstream side. The boat would ride in a tub that would accommodate one craft 24 ft or less in length.

c. Twenty of the Upper Mississippi River locks have partial provisions for a second lock chamber, 100 ft by 360 ft. These provisions include an upper gate sill, upper portion of the river wall, and recesses in the intermediate wall for the lower miter gate and gate machinery. Completion of this lock chamber would involve damming and dewatering the chamber area; removing accumulated debris and providing scour protection measures; constructing the river wall and chamber floor; removing and rehabilitating the upper miter gate; and installing gates, valves, operating machinery, and appurtenances. Commercial traffic would also be able to use the new lock if the main chamber fails.

d. Eighteen of the twenty Upper Mississippi River locks with partial provisions for a second lock chamber include either a roller or tainter flood control gate adjacent to the river wall. At these 18 locks, the completion of a 400-ft auxiliary lock would be possible. The 400-ft chamber would be built by extending the river wall, Dam Pier 2, and possibly the intermediate wall downstream. A new miter gate and tainter gate would be built in a monolith at the lower end of the chamber. The wall and pier extensions would be made from steel sheet-pile cells. The extension of the dam pier and any extension of the intermediate wall would be a solid cell wall. The river wall would be steel sheet-pile cells spaced with 10-ft clearances between cells. The monolith would be keyed into the intermediate wall and the dam pier extension. The area between the river wall and the dam pier extension would function as a flume to fill the lock chamber (the area between the river wall and the intermediate wall). Commercial traffic would be able to use the new chamber if the main chamber fails.

e. A mobile floating lock is a self-contained, fully operational lock structure that can be positioned behind the existing upper miter gates for the auxiliary chamber. This device would be approximately the size of three barges abreast (105 ft by 200 ft). The lock is a steel vessel similar to a dry dock. The sides would be floating tanks housing the operating machinery and controls. The upper and lower gates, integral parts of the dock, would be permanently mounted within the outside tanks. The upper and lower gate types have not been determined but would probably be submerging tainter gates or hinged drop gates, depending on the available depth in the chamber. Filling and emptying would be done through ports in the chamber floor.

f. The small-scale steel lock, 25 ft by 80 ft, would be a double-wall steel structure of 3/8-in. plate with adequate diaphragms. The upper gate bay would include a vertical lift gate and an emptying system. The upper sill elevations would be set to accommodate sailboats up to 40 ft long.

g. The 25-ft by 80-ft concrete and sheet-pile lock would be a concrete U-frame structure on a sand foundation. The structure would include a concrete upper gate bay monolith, a lower concrete gate bay monolith, and a lock chamber of sheet-pile walls with a revetment floor. The inside face of the cofferdam would act as the outer form for the concrete gate bay monoliths and would be constructed on site.

h. The differential railway lift consists of a steel tank (pan) carried up an inclined plane, over a crest, and down a reverse plane without being tilted. The pan is rigidly suspended from a carriage equipped with two sets of wheels to travel on a system of track elevated over the earth dike. The outer set of wheels maintains the pan horizontally while the carriage travels above the downstream face of the dike on a 2.5H to 1V incline. The inner set of wheels maintains the pan horizontally while the carriage travels above the upstream face of the dike on a reverse 2.5H to 1V incline. Both sets of wheels are used as the carriage travels above the crest on a double set of differential rails.

i. The steel tank on inclined rails consists of a steel tank (pan) supported by an overhead crane at each corner. The cranes lift the tank vertically out of the water, travel horizontally along rails across the dike, and then lower the tank into the water on the other side. The

crane trolleys on each rail are structurally separated from the trolleys on the other rail and each uses one drive wheel. The four lift motors and both crane drives are electrically synchronized, eliminating overhead clearance restrictions.

j. The mobile boat carrier system is based on a mobile boat carrier presently used for launching certain pleasure craft. The slings could be replaced with a tank (pan) for holding the boats being transported. The modified boat carrier would lift the tank out of the water, travel along a horizontal track across the dike, and lower the tank into the water on the reverse side. The carrier cross member would restrict the overhead clearance. Additional studies would be required to determine if the slings could be safely adapted to various boat shapes.

k. The inclined channel lift is similar to a device in operation at Montech, near Toulouse, France, connecting two canals. Two water levels in the canal are joined by a 480-ft flume or concrete ramp having a U-shaped section. Water at the upper level is held back by a tilting gate. The boat on the lower level enters the approach basin. A large plate at the end of two arms is lowered into the water behind the boat, forming a wedge-shaped body of water in which the boat floats. The plate is then pushed forward by two 1,000-horsepower diesel-electric locomotives, one on each bank.

l. The inclined plane lift resembles Belgium's Ronquieres ship lift located near Brussels. This single structure is 4,700 ft long and raises and lowers craft 225 ft. Two inclined planes raise and lower 1,500-ton barges 225 ft in 22 min. Barges enter a tank (pan) with gates at either end and are pulled or lowered by six 125-kilowatt electric motors connected to the tanks by eight 2.25-in.-diam cables. When loaded, the tanks weigh between 5,500 and 6,280 tons. Counterweights weighing 5,733 tons run up and down in recesses between the tank rails. The tanks measure 49 ft by 300 ft and are 14 ft deep. Both tanks and counterweights ride spring-suspended on flangeless wheels running on steel rails.

m. The version considered for the Upper Mississippi River would have one tank approximately 26 ft by 80 ft and maintain a depth of about 4 or 5 ft. The system would be operated by remote control from the main lock and monitored by television and two-way radio communication.

# Appendix H

## Notation

Symbol	Definition	Dimensions	Symbol	Definition	Dimensions
			$d_e$	Overtravel of lock water surface below lower pool	ft
$a$	Variable cross-sectional culvert area	ft <sup>2</sup>	$d_f$	Overtravel of lock water surface above upper pool	ft
$a_i$	Discrete values for area, $a$	ft <sup>2</sup>	$dz/dt$	Rate of change of the chamber surface elevation	ft/sec
$A$	Reference cross-sectional orifice area	ft <sup>2</sup>	$D_c$	Lock chamber depth	ft
$A_c$	Reference cross-sectional culvert area	ft <sup>2</sup>	$D_h$	Hydraulic diameter	ft
$A_L$	Lock-chamber water-surface area	ft <sup>2</sup>	$D_s$	Sill depth	ft
$A_p$	Total port area	ft <sup>2</sup>	$f$	Darcy-Weisbach friction factor	none
$b$	Tainter gate opening (vertical)	ft	$g$	Gravitational acceleration	ft/sec <sup>2</sup>
$b_g$	Sector gate opening (horizontal)	ft	$\Delta h_{a-b}$	Piezometric head at location $a$ minus piezometric head at location $b$	ft
$B$	Culvert height at valve location	ft	$h$	Piezometric head; upper level referenced to the upper sill	ft
$B_i$	Culvert height in expanded section	ft	$H$	Water-surface differential (static pools)	ft
$B_i^*$	Effective culvert expansion height	ft	$H_{Li}$	Apparent loss of total head in system "i". Note: intake ( $i=1$ ); upstream culvert ( $i=2$ ); valve ( $i=v$ ); downstream culvert ( $i=3$ ); outflow ( $i=4$ ); remote segments ( $i=5$ ); overall( $i=t$ )	ft
$c$	Slot discharge coefficient	none	$H_m$	Overall inertial effect	ft
$C$	Orifice discharge coefficient	none	$k_i$	Loss coefficient. Note: intake ( $i=1$ ); upstream culvert ( $i=2$ ); valve ( $i=v$ ); downstream culvert ( $i=3$ ); outflow ( $i=4$ ); remote segments ( $i=5$ ); manifold ( $i=m$ ).	none
$C_c$	Contraction coefficient	none			
$C_L$	Overall lock coefficient	none			
$d$	Draft of vessel	ft			

30 Jun 95

Symbol	Definition	Dimensions	Symbol	Definition	Dimensions
$k_t$	Energy loss coefficient	none	$t_m$	Time at which maximum rate of rise of lock water surface occurs	sec
$K$	Overall valve coefficient (not a loss coefficient)	none	$t_v$	Time at which valve is fully open	sec
$L$	Length	ft	$T$	Operation time	sec
$L_m$	Inertial length	ft	$v$	Velocity in wall culverts through the full open valve	ft/sec
$n$	Number of valves used, 1 or 2	none	$V$	Mean velocity at the reference section	fps
$P_c$	Culvert perimeter at the reference section	ft	$z$	Elevation	ft referred to datum
$Q$	Flow rate; discharge per culvert	cfs	$Z_l$	Lower water-surface elevation	ft referred to datum
$Q_T$	Total discharge	cfs	$Z_r$	Culvert roof elevation	ft referred to datum
$r$	Model scale ratio		$Z_U$	Upper water-surface elevation	ft referred to datum
$R$	Reynolds number	none	$Z(t)$	Lock water-surface elevation at time $t$	ft referred to datum
$t$	Time	sec	$\alpha$	Flow ratio	none
$t_c$	Time at which the water surface reaches overtravel below lower pool	sec	$\nu$	Kinematic viscosity	ft <sup>2</sup> /sec
$t_f$	Time at which the water surface reaches maximum overtravel above upper pool	sec			